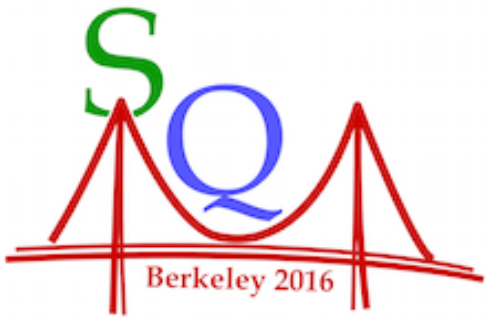
# Recent Heavy Flavor Results Utilizing the FVTX in PHENIX at RHIC

Xuan Li (LANL)

For the PHENIX Collaboration




Strangeness in Quark Matter 2016

from 27 June 2016 to 1 July 2016
UC Berkeley
US/Pacific timezone

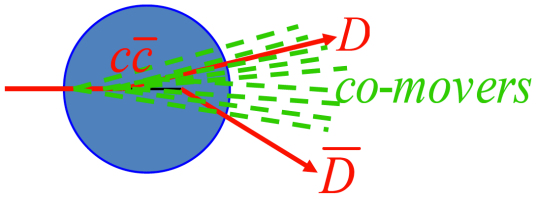
# Outline

- Motivation
- Silicon Vertex Detectors of PHENIX
- Selected PHENIX measurements
  - Forward J/ψ and ψ' ratio via di-muon channel in p+p, p+Al and p+Au collisions.
  - Forward B to J/ψ ratio via di-muon channel in p+p and Cu+Au collisions.
- Summary and Outlook

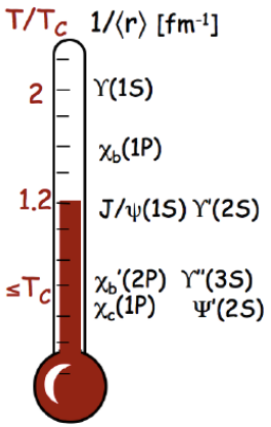
# Motivation

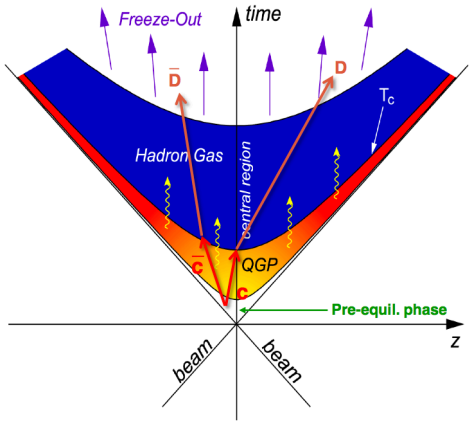
- Heavy flavor is a good probe to study the full evolution of the medium as it is produced in the early stage of nuclear collisions due to its high mass ($m_c$, $m_b$>>$\Lambda_{QCD}$).
- Quarkonia are expected to dissociate sequentially in the QGP due to color screening melt in later stage, and can be treated as a thermometer to probe the QGP temperature.
- Interaction with the medium (Cold Nuclear Matter/ Hot Nuclear Matter) is not well understood.

CNM effect: co-mover absorption




Hot Nuclear effect: QGP formation

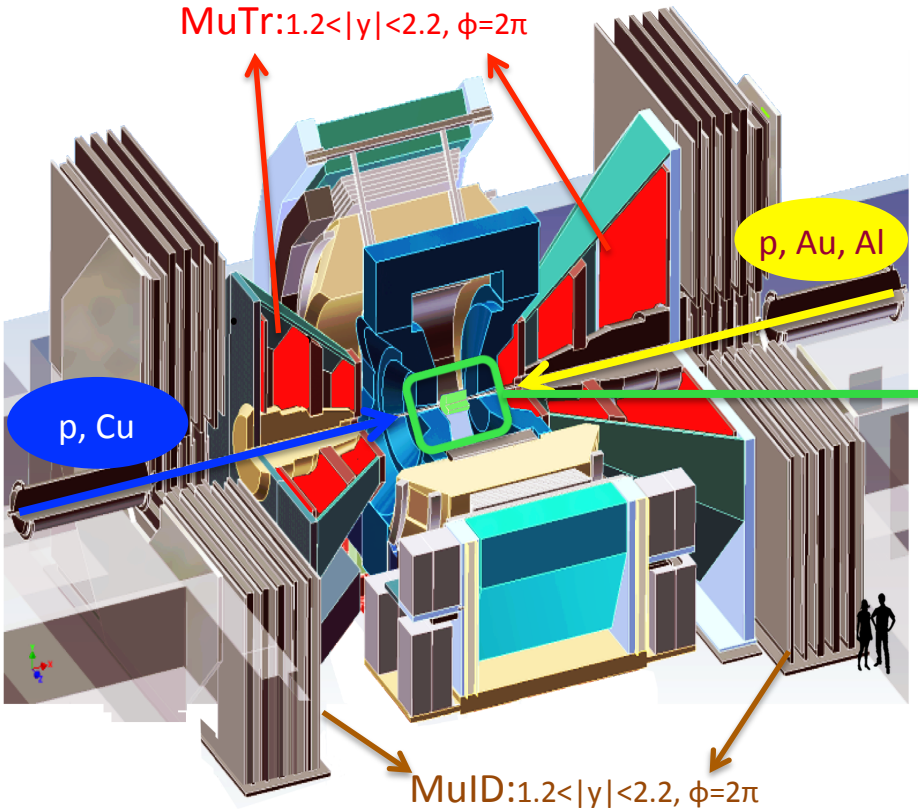


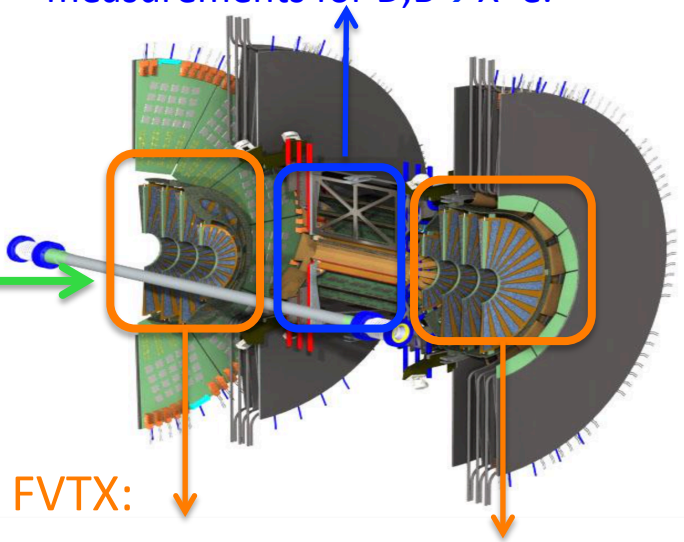

- Need to measure multiple observables in different processes to isolate the initial/final state and cold/hot nuclear matter effects.

# Silicon Vertex Detectors of PHENIX

- The silicon vertex detectors: VTX(installed since 2011) and FVTX(installed since 2012) make the new heavy flavor measurement possible in p+p, p+Al, p+Au, Cu+Au and Au+Au collisions.



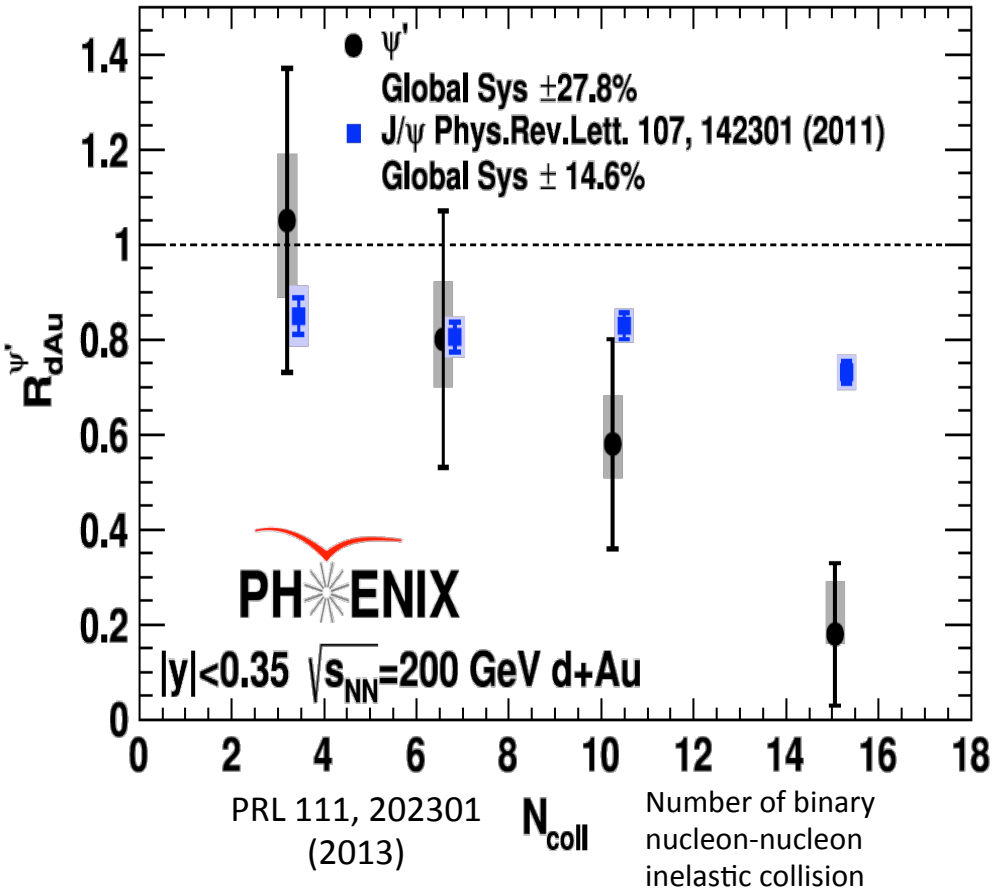

- VTX:
  - With |y|<1.2 and ϕ≈2π coverage.
  - provide precise vertex and tracking measurements for D,B→X+e.



- FVTX:
  - With 1.2<|y|<2.2 and ϕ=2π coverage.
  - provide precise tracking and improved resolution for di-muon mass measurements for J/ψ, ψ' →$\mu^+\mu^-$,B→J/ψ and D, B separation.

# Explore the CNM effect via charmonia (J/ψ and ψ')

- Mid-rapidity ψ' $R_{dAu}$ measured at PHENIX in d+Au collisions has different trend and magnitude of suppression versus $N_{coll}$ from the J/ψ results.



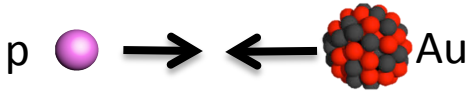

PRL 111, 202301 (2013)

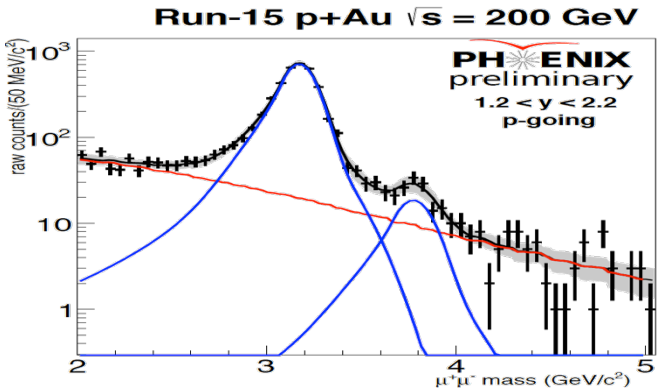
Number of binary nucleon-nucleon inelastic collision

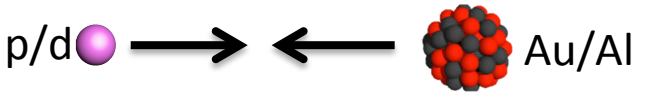
- Similar initial state effect (shadowing, energy loss etc.) on J/ψ and ψ'.
- Indications of impacts from final state effects cause the difference.
- Can we study this in forward/backward rapidity and different collision system?

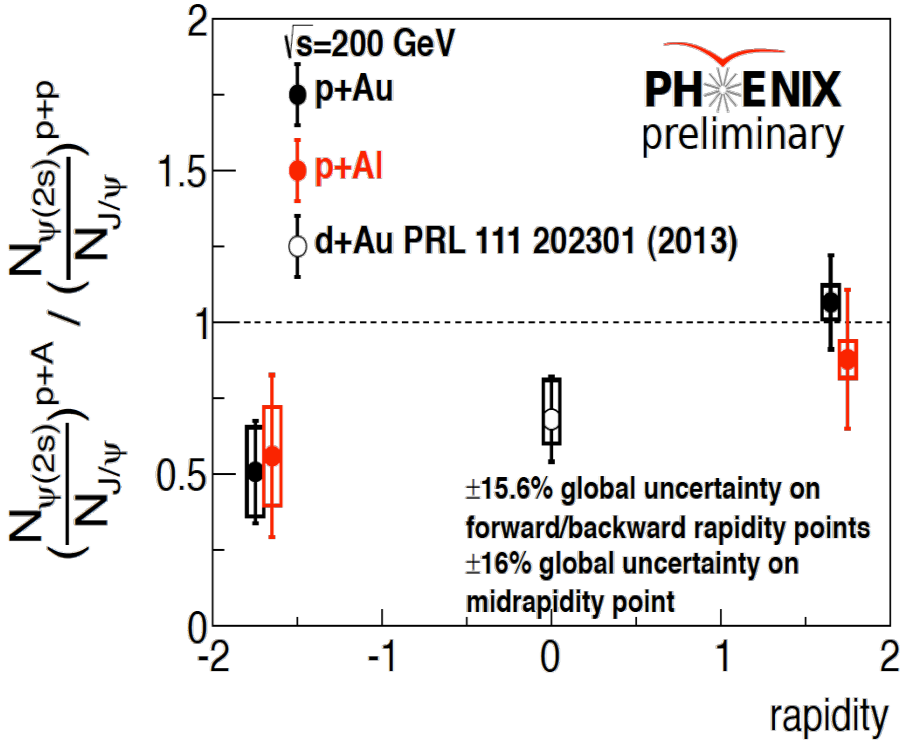
# Relative ratio of ψ' to J/ψ vs rapidity

- Centrality-integrated relative ratio of ψ' to J/ψ vs rapidity for forward and backward p+Au, p+Al and mid-rapidity d+Au.



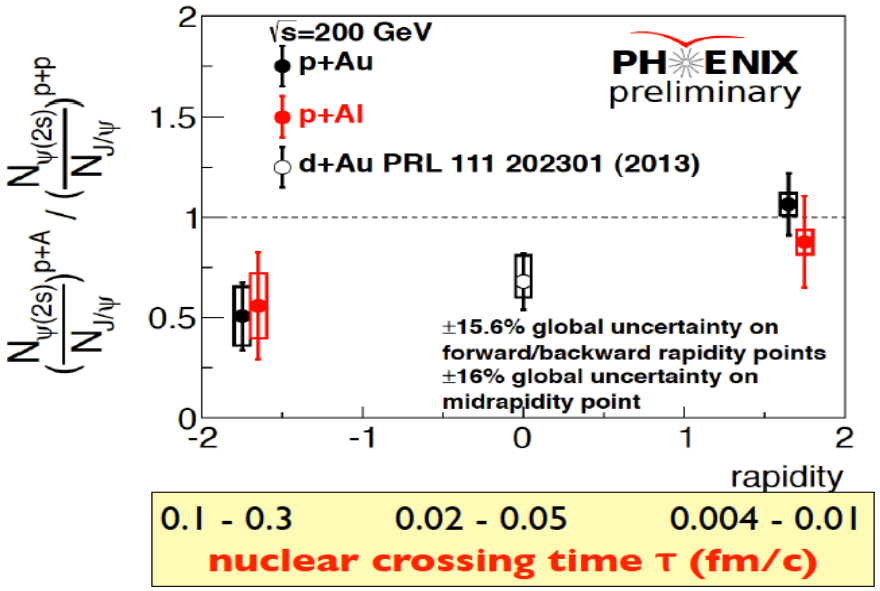



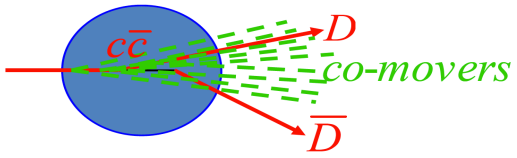

- The J/ψ and ψ' have similar suppression at forward rapidity.
- Strong relative suppression is observed at back rapidity.

# Possible contributions to the differential suppression

- Time spent inside the nucleus
  - Longer time and path length spent by the cc-bar in Au- (Al-) going direction than the p- going direction.



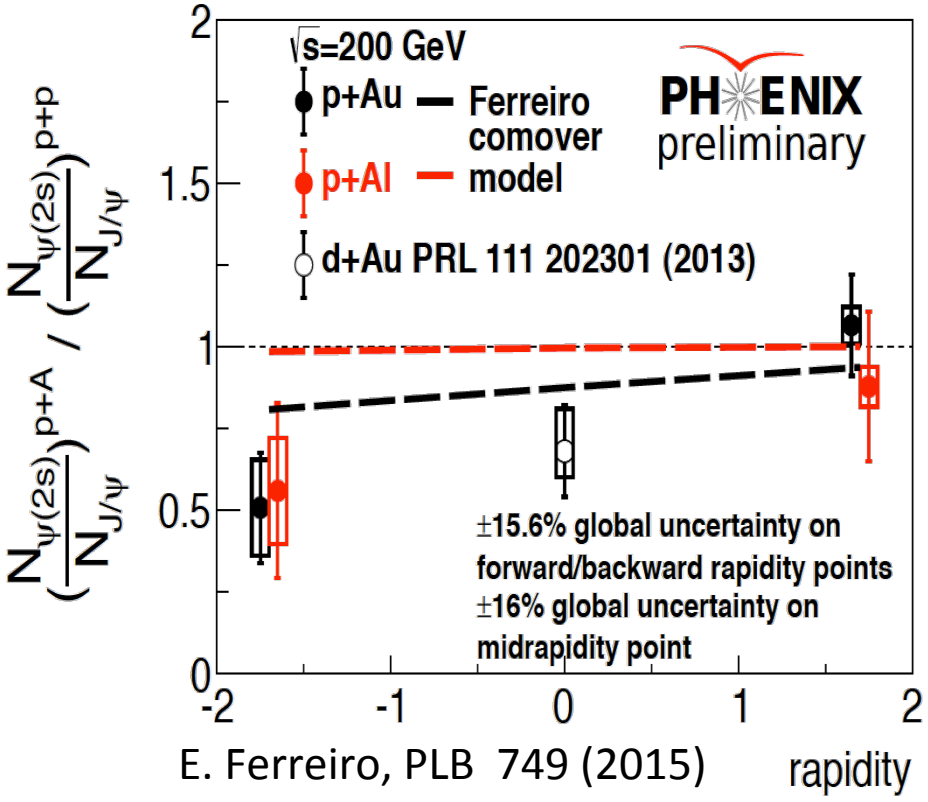

  - According to the crossing time τ dependent model fit on world wide data (PRC 87 (2013) 054910), very small contributions.
  - This effect can not explain the backward rapidity suppression.




- Absorption by Co-movers?
  - Charmonium can break up in the presence of co-movers.
  - Higher particle density in the Au- (Al-) going direction may cause larger suppression.

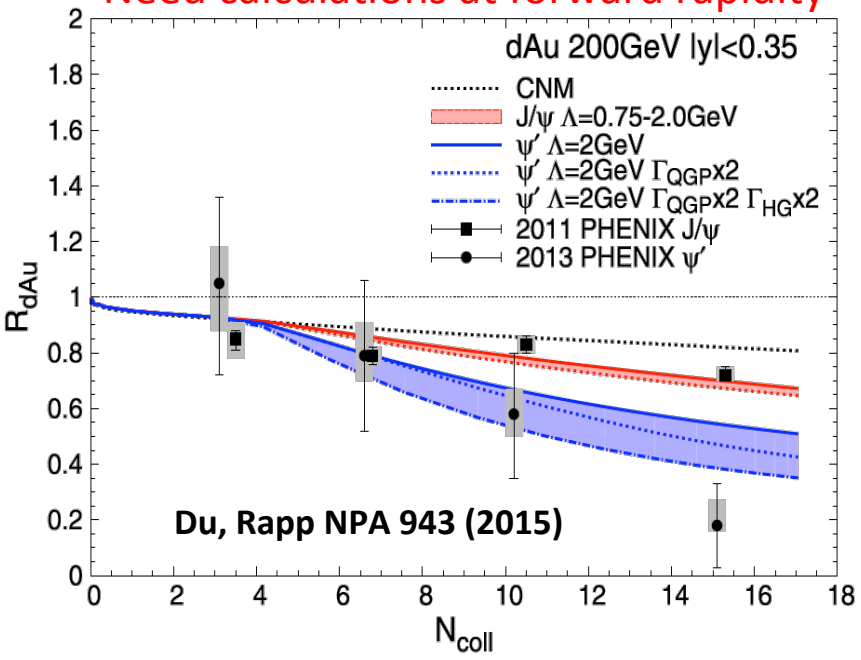
# Relative ratio of ψ' to J/ψ vs rapidity

- Centrality integrated relative ratio of ψ' to J/ψ vs rapidity for p+Au, p+Al and d+Au (mid-rapidity).




E. Ferreiro, PLB 749 (2015)

Need calculations at forward rapidity



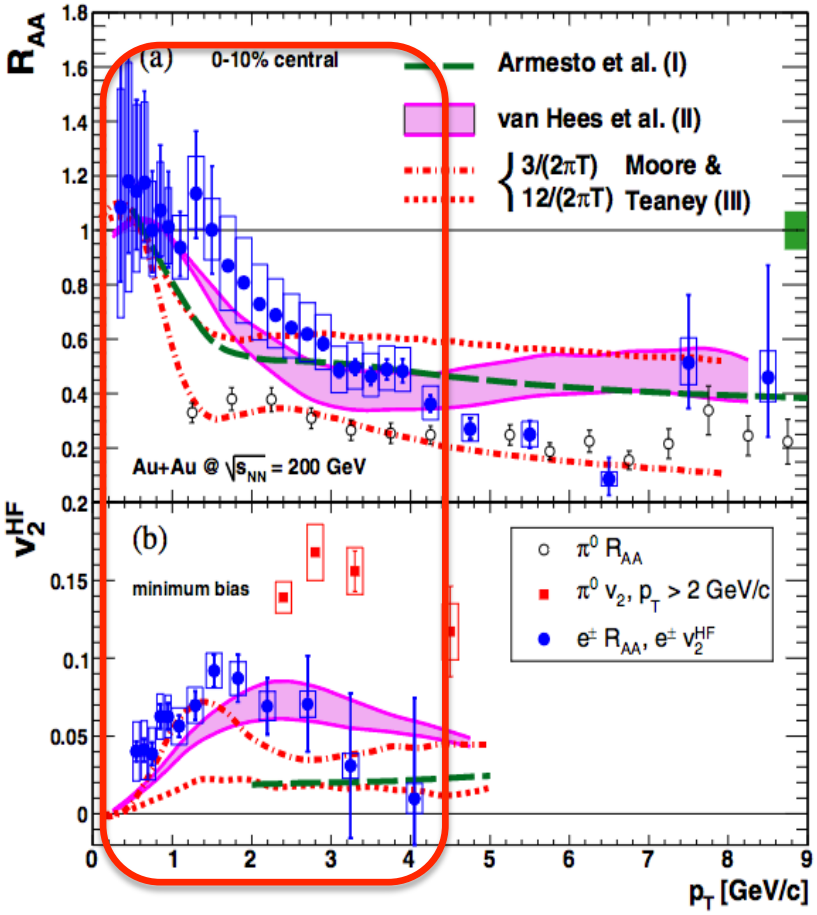

New calculation allows for short QGP phase in central collisions + hadron resonance gas.

- The trend of the rapidity dependency is consistent with co-mover dissociation model.
- New model calculations? Plasma effect in central collisions?

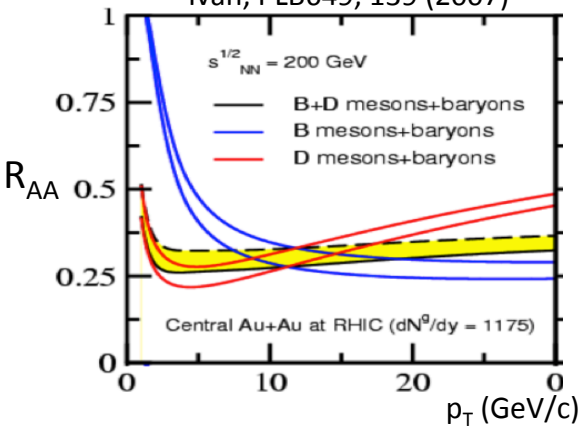
# Study the Hot Nuclear Matter effect via open heavy flavor production

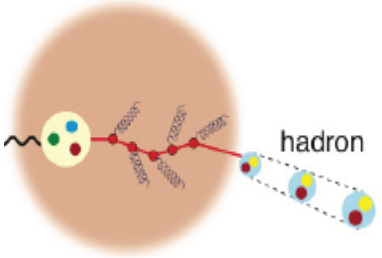
- Suppression of the inclusive Heavy flavor $R_{AA}$ provides evidence of strong coupling between the heavy flavor and medium.

PRL 98, 172301 (2007)




Ivan, PLB649, 139 (2007)



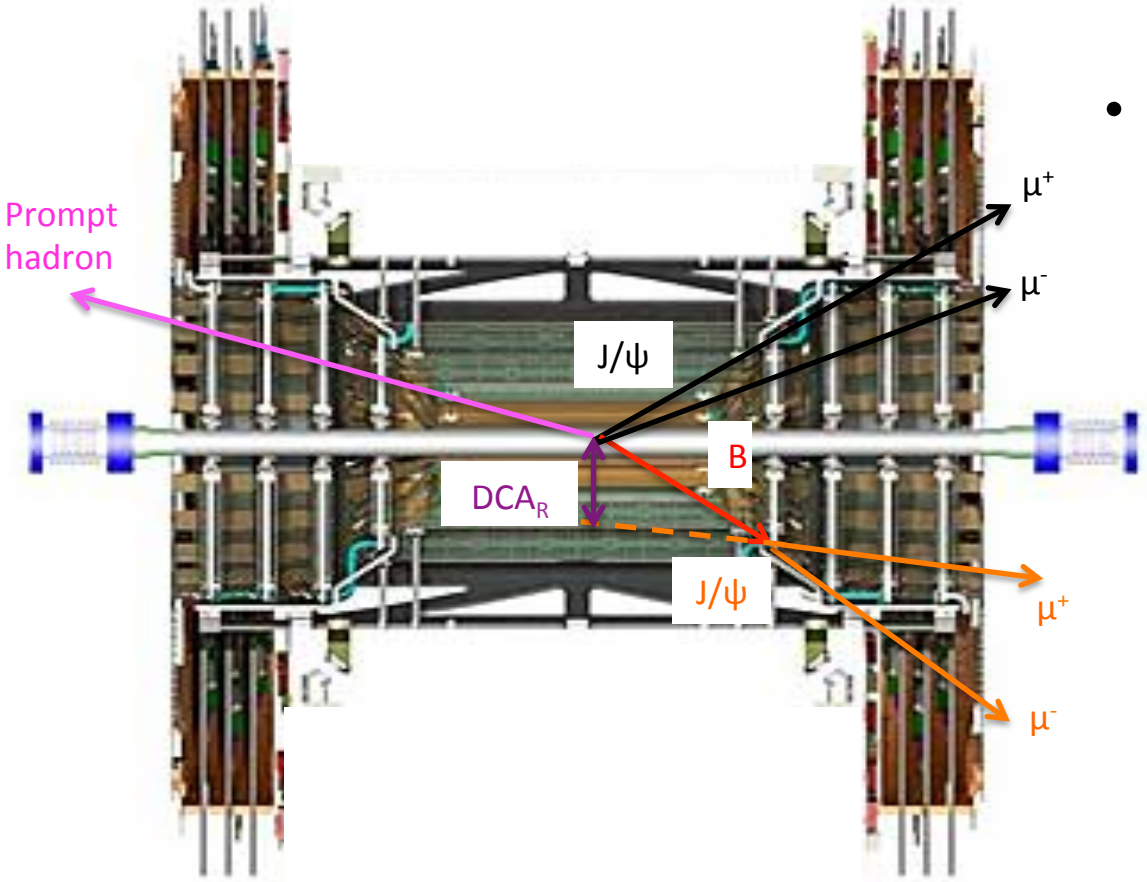




- Low $P_T$ heavy flavor production is dominated by charm production, need to separate charm and bottom and study the mass/flavor dependent quark energy loss.
- Measure B-meson directly?

# Can we measure B meson in forward rapidity?

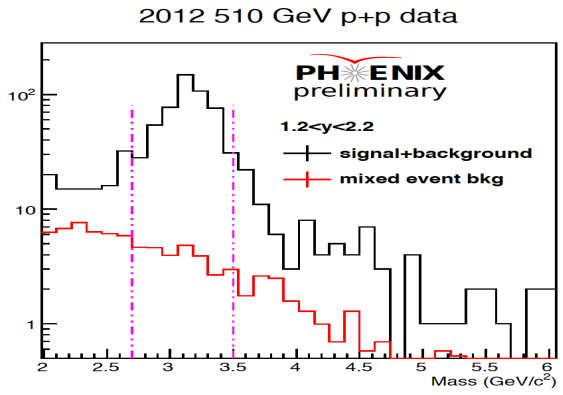
## B->J/ψ->$\mu^+\mu^-$

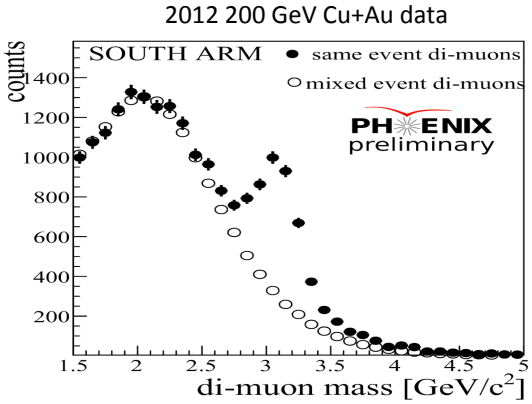
- B mesons measured in the forward/backward rapidity with longer decay length may probe different QGP evolution stage in heavy ion collisions from the mid-rapidity region.




- Different shapes of the Distance of Closet Approach along the radial projection ($DCA_R$) of prompt particles and decayed particles make the separation of B decayed J/ψ and prompt J/ψ feasible.

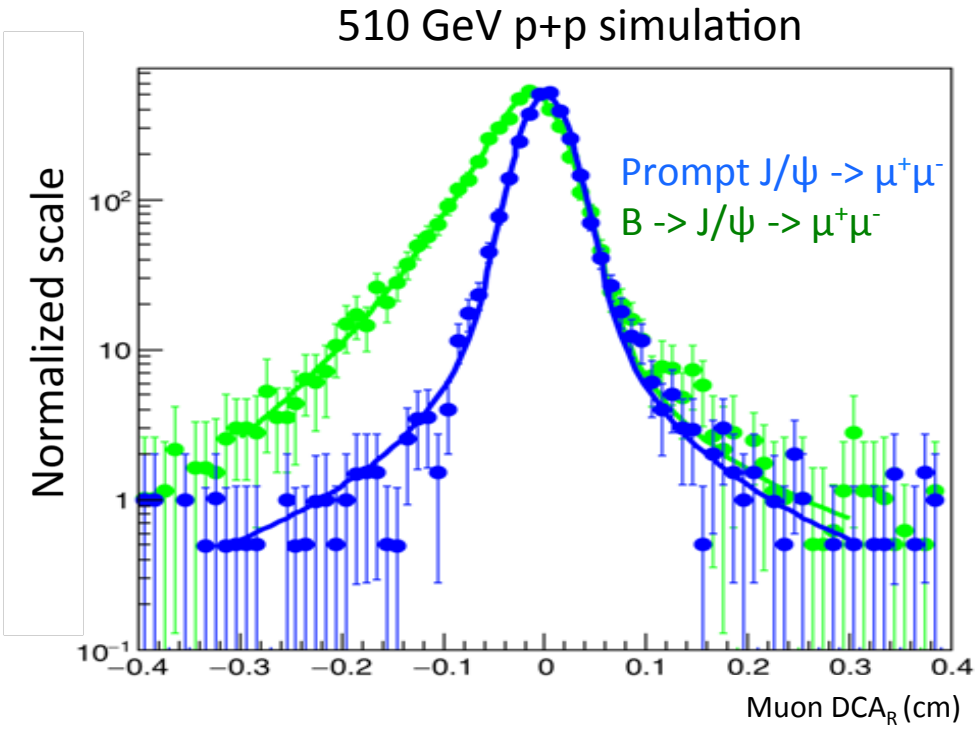
# Analysis strategy for the B to J/ψ ratio measurement (I)



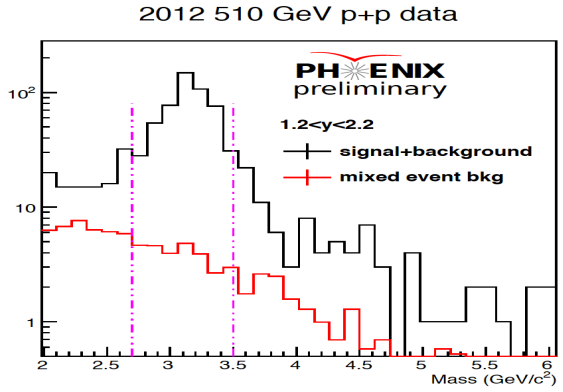



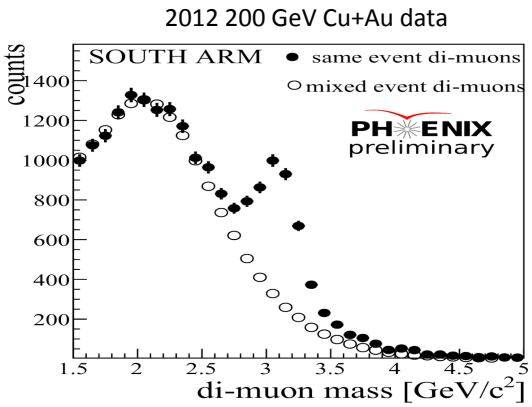

- Clear J/ψ peaks are found in both p+p and Cu+Au data.

- Signal determination
  - Generate prompt J/ψ and B to J/ψ events in full simulation (PYTHIA +GEANT+RECO) for p+p with realistic vertex and dead maps etc.
- Obvious $DCA_R$ shape difference between prompt J/ψ and B to J/ψ.



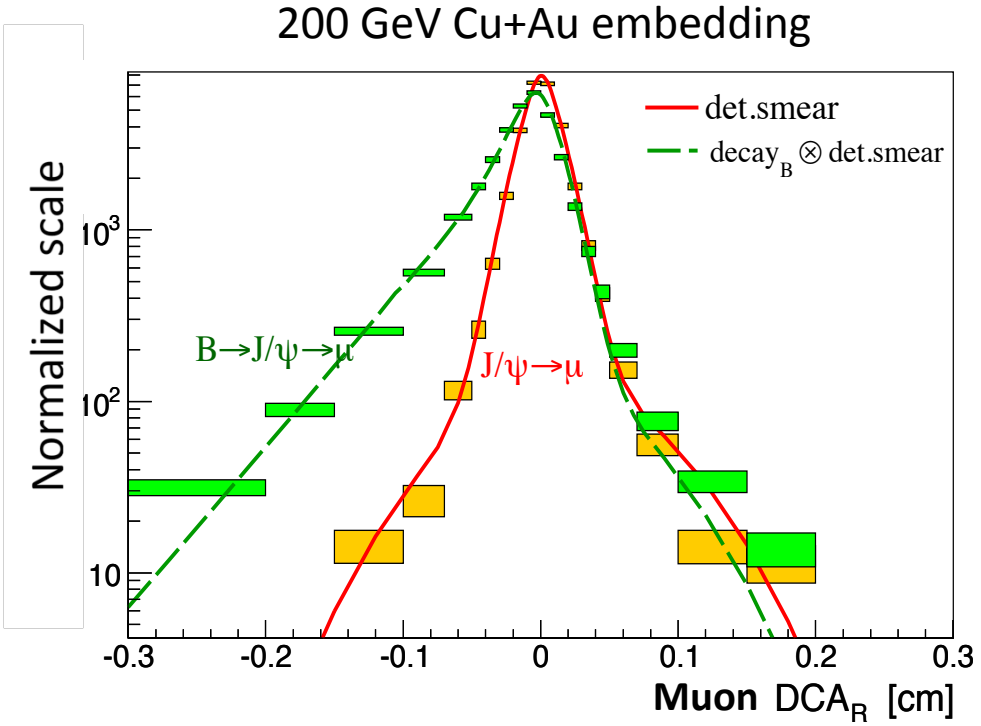
# Analysis strategy for the B to J/ψ ratio measurement (II)



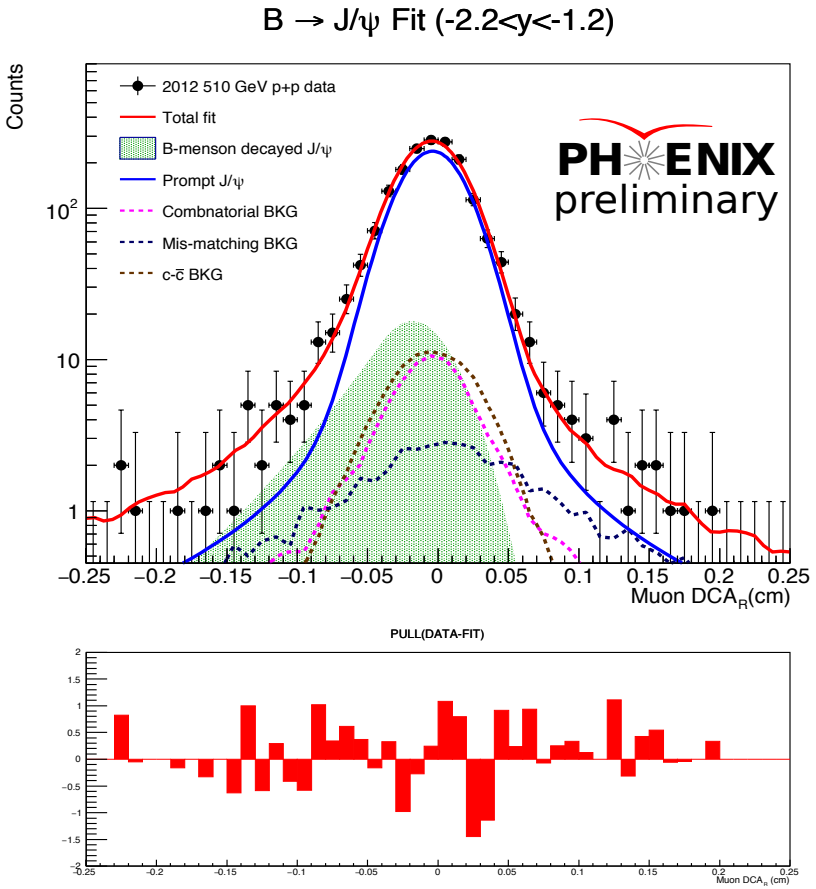

- Clear J/ψ peaks are found in both p+p and Cu+Au data.

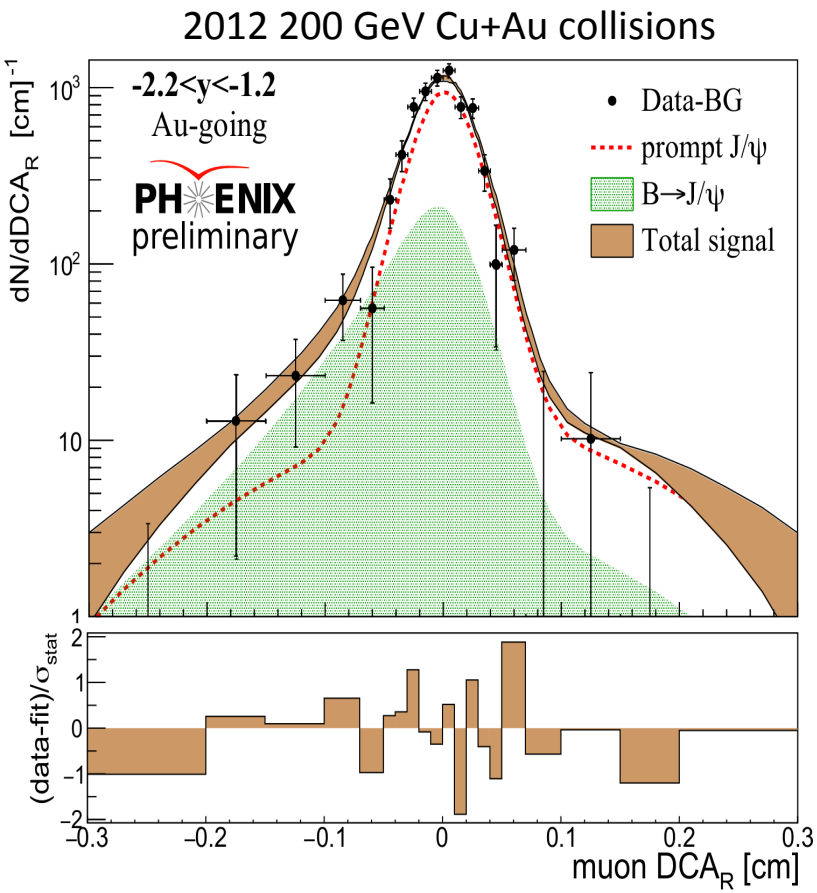
- Signal determination
  - Generate prompt J/ψ and B to J/ψ events in embedding for Cu+Au with realistic vertex and dead maps etc.
- Obvious $DCA_R$ shape difference between prompt J/ψ and B to J/ψ.



# Analysis strategy for the B to J/ψ ratio measurement (III)

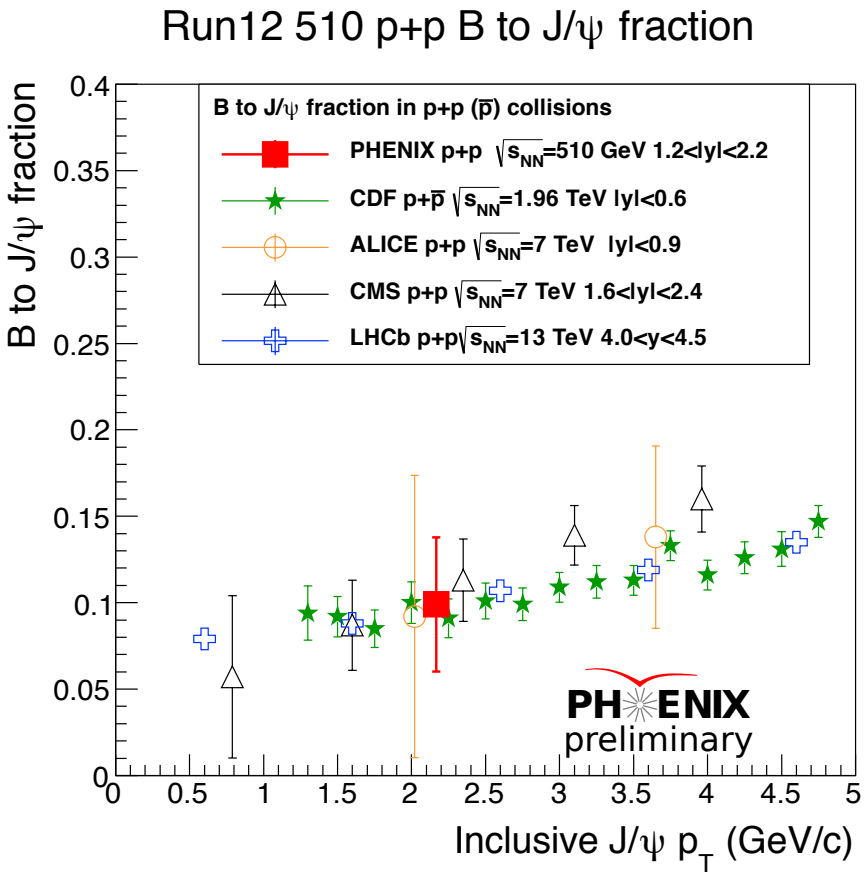
- Fit on $DCA_R$ in data to simultaneously determine the prompt J/ψ and J/ψ from B-meson decay yields and extract the B to J/ψ fraction.

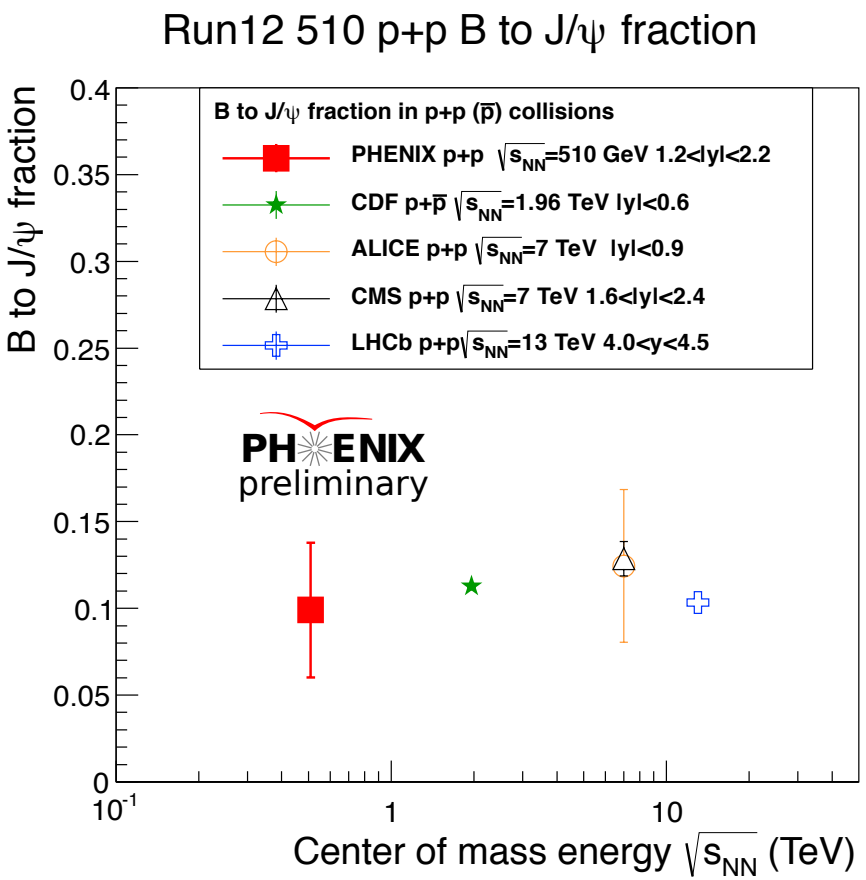


# B->J/ψ fraction in 510 GeV p+p data

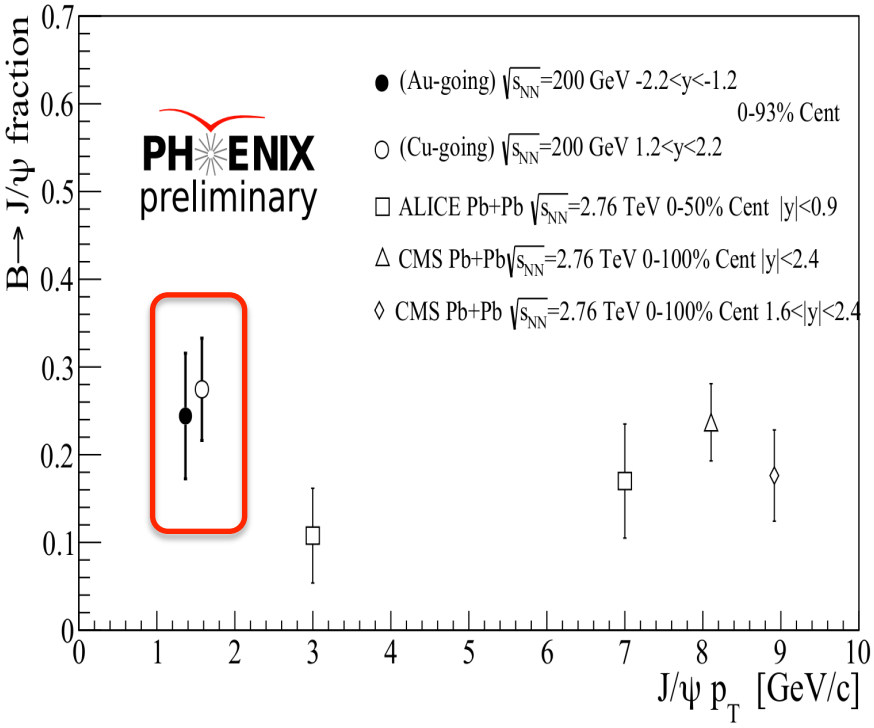
- The B->J/ψ fraction does not have a strong energy dependence for J/ψ $p_T$ < 5GeV/c region.
- Indicate that 200 GeV p+p baseline follows the same trend?

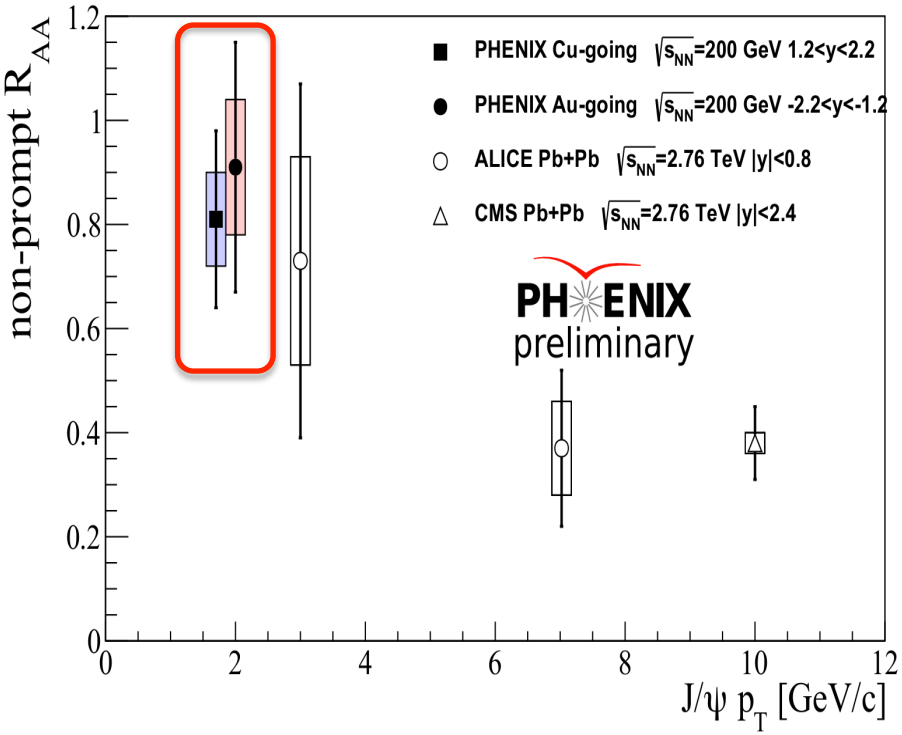


# B->J/ψ fraction in 200 GeV Cu+Au data

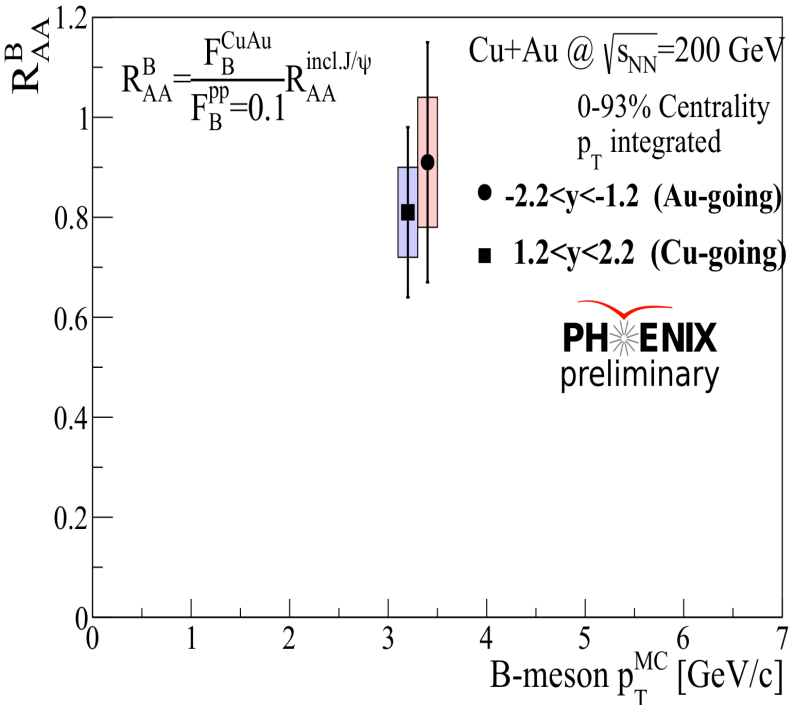
- The B->J/ψ fraction measured in the Cu+Au collisions at PHENIX is much larger than the LHC results.
- Assuming the fraction is 0.1 in 200 GeV p+p collisions, the $R_{CuAu}$ defined as $R_{CuAu}^{B\to J/\psi} = \frac{F_{B\to J/\psi}^{CuAu}}{F_{B\to J/\psi}^{pp}=0.1} R_{CuAu}^{inc.J/\psi}$ is less suppressed.
- PHENIX and LHC $R_{AA}$ follow the same trend.

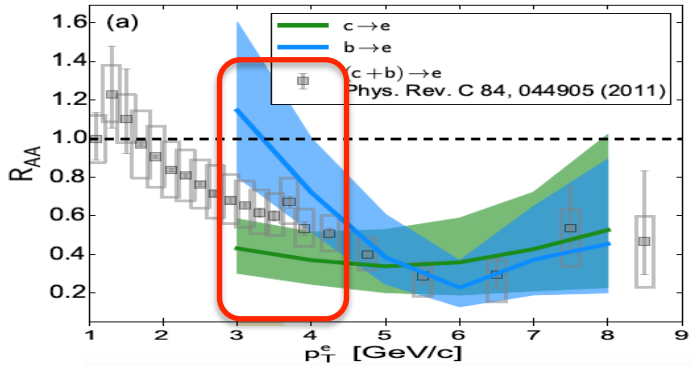


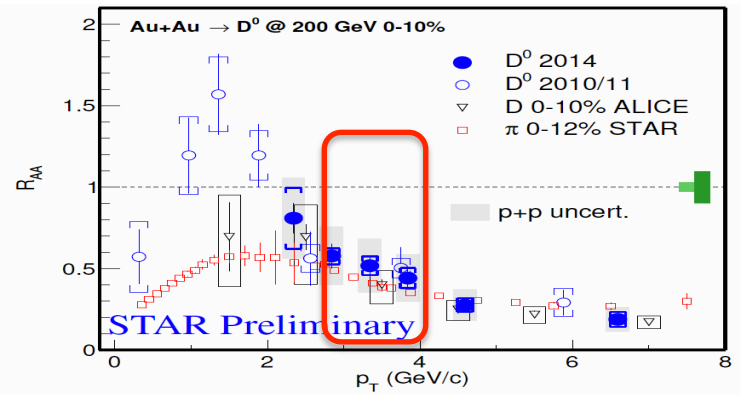



# B->J/ψ $R_{AA}$ in 200 GeV Cu+Au data

- Cu-going/Au-going B-meson $R_{CuAu}$ measured in Cu+Au data agrees with the PHENIX mid-rapidity electron $R_{AuAu}$ from bottom decay, and is different from STAR $D^0$ $R_{AuAu}$ at the same energy.
- Is bottom production less suppressed than the charm production in the forward rapidity in the low $p_T$ region?




PRC 93, 034904 (2016), QM15

# Summary

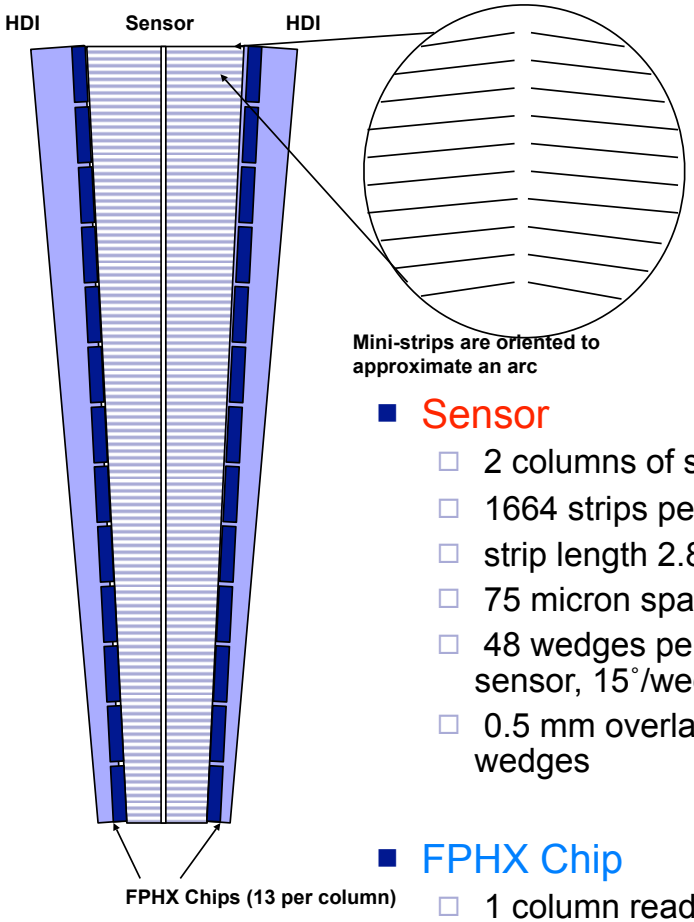
- Differential suppression of ψ′ to J/ψ relative ratio in p+Al and p+Au data shows strong evidence of final state effects.
  - The co-mover model provides a reasonable description.
  - Other theory calculations?
- First measurement of J/ψ from B decays in forward/backward rapidity at low $p_T$ are achieved in both 510 GeV p+p and 200 GeV Cu+Au collisions.
  - No center of mass energy dependence for low $p_T$ J/ψ from B-meson decay in p+p collisions.
  - Small nuclear modification of integrated $p_T$ and centrality averaged B-mesons in Cu+Au data, which is in agreement with other measurements and theory.

# Outlook

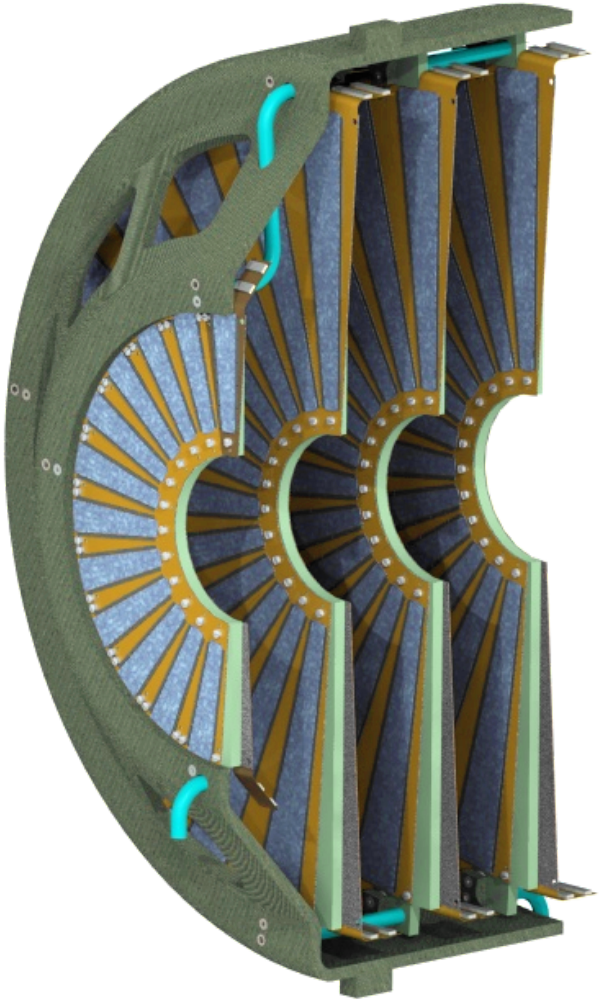
- Large data set in various types of heavy ion collisions collected at PHENIX provide opportunities to study
  - $\psi'$ to J/$\psi$ ratio in run14/16 Au+Au collisions to demonstrate hot nuclear matter effect like color screening in QGP.
  - Study the D/B separate single muons in run12/15 p+p, run15 p+Au and run14/16 Au+Au collisions with higher statistics.
  - Forward/backward B to J/$\psi$ via di-muon channel in run15 p+p, p+Au, run14/16 Au+Au collisions to understand CNM and hot nuclear matter effect.
- More nice results to come.

# Backup

# The Forward Vertex Detector (FVTX)

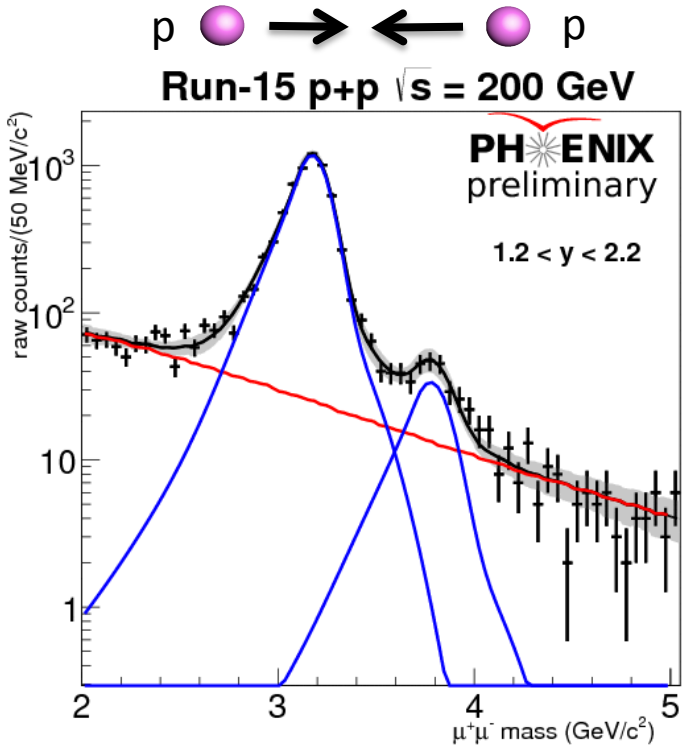


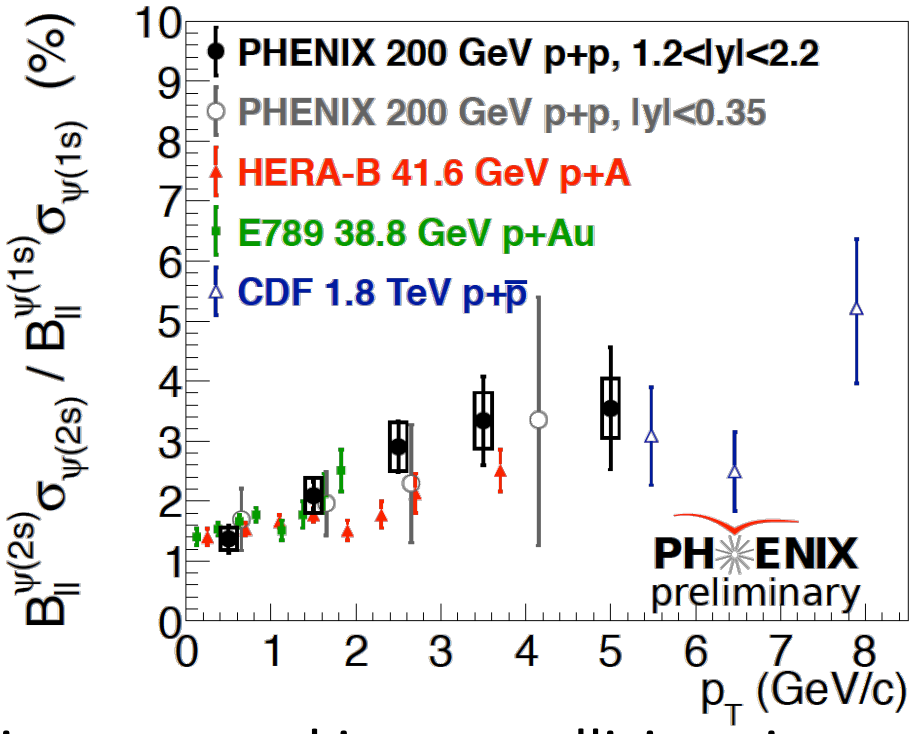

- Sensor
  - 2 columns of strips
  - 1664 strips per column
  - strip length 2.8 to 11.2 mm
  - 75 micron spacing
  - 48 wedges per disk (7.5˚/ sensor, 15˚/wedge)
  - 0.5 mm overlap with adjacent wedges
- FPHX Chip
  - 1 column readout
  - 128 channels
  - ~ 70 microns channel spacing
  - Dimensions –9mm x 1.2 mm



# Forward J/ψ and ψ' measurement in p+p collision

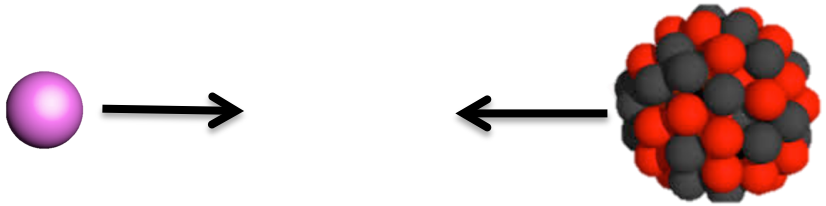
- With improved mass resolution provided by FVTX, clear J/ψ and ψ' identification via di-muon channel (1.2<|y|<2.2) in run15 200 GeV p+p data.

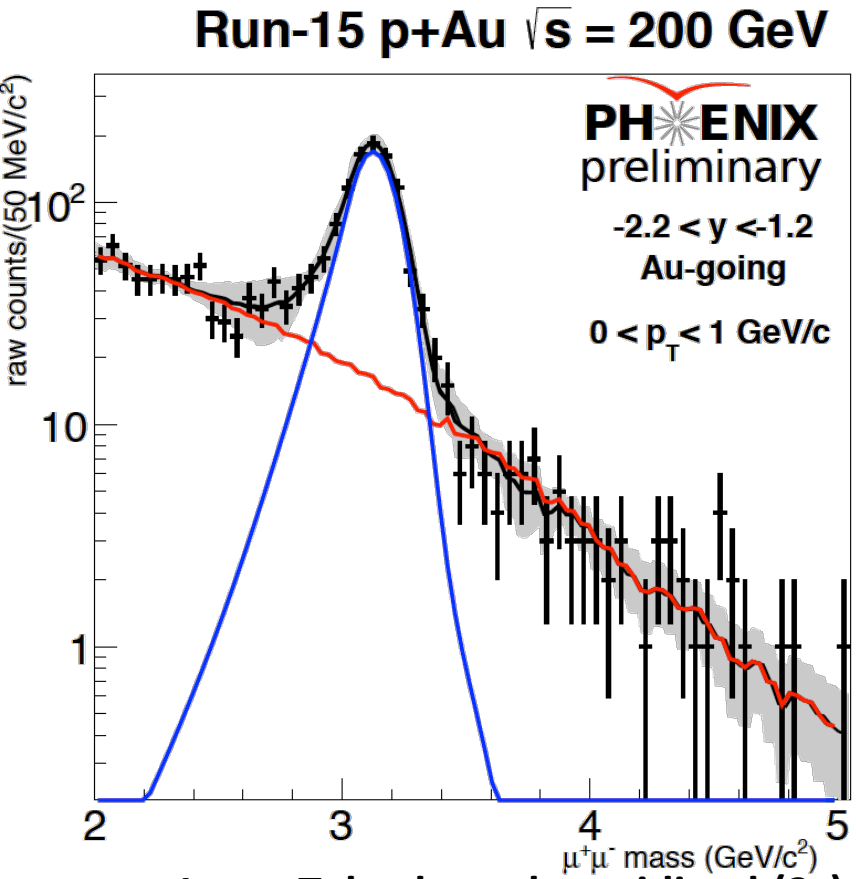


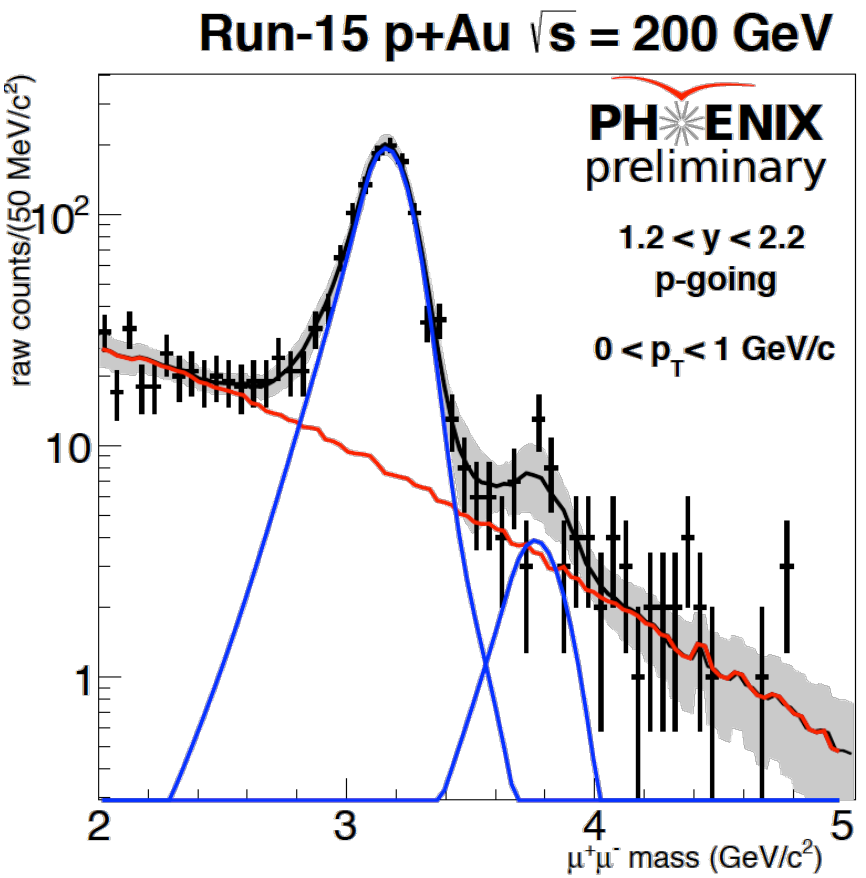




- The forward ψ' to J/ψ ratio measured in p+p collisions is consistent with the global data.

# p+A pT dependence



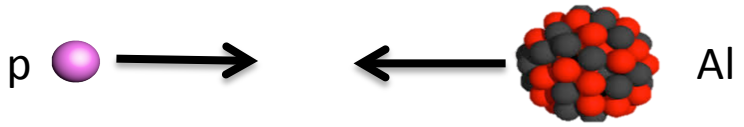


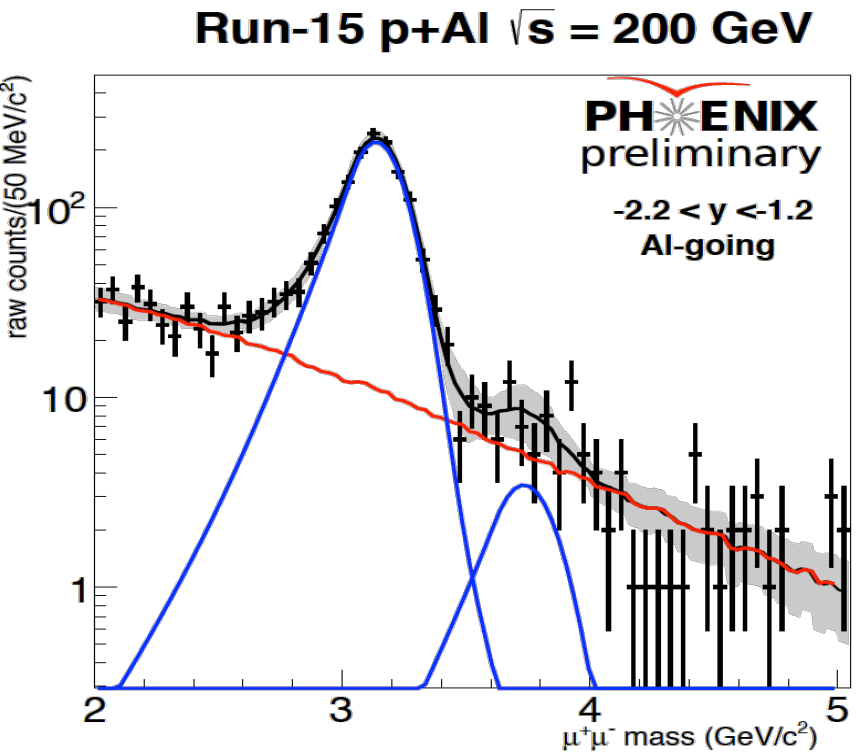



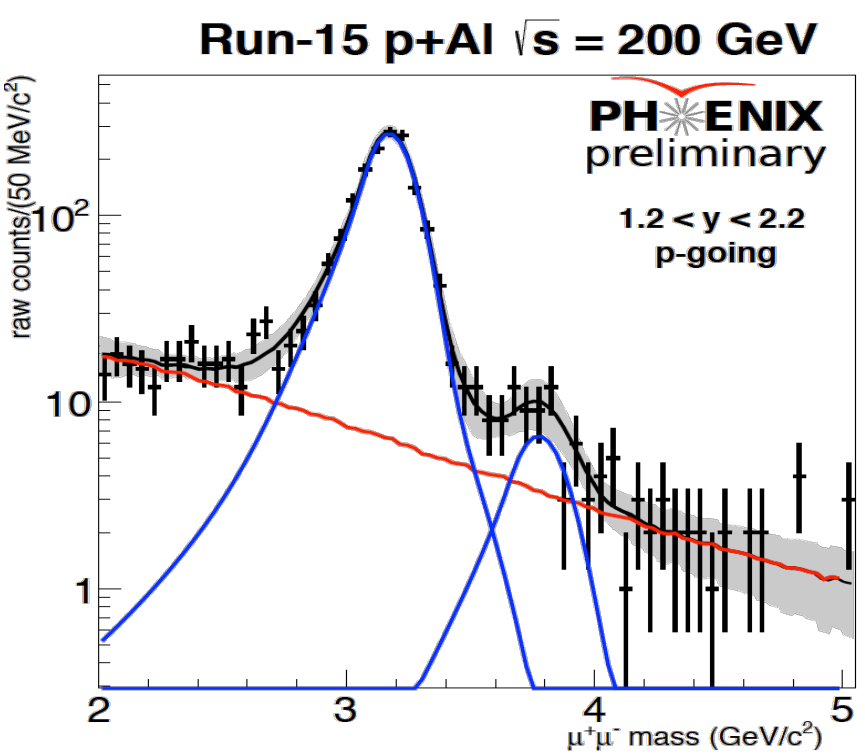

**Low pT, backwards rapidity ψ(2s) yields *consistent with ZERO.***

# How about asymmetric nuclear collisions?

- In 200 GeV p+Al collisions.



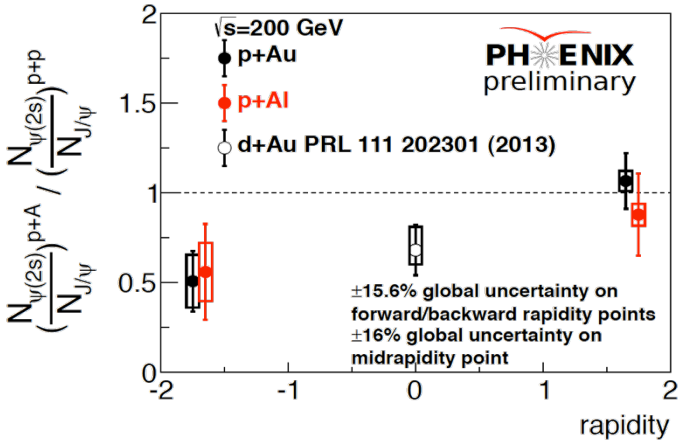



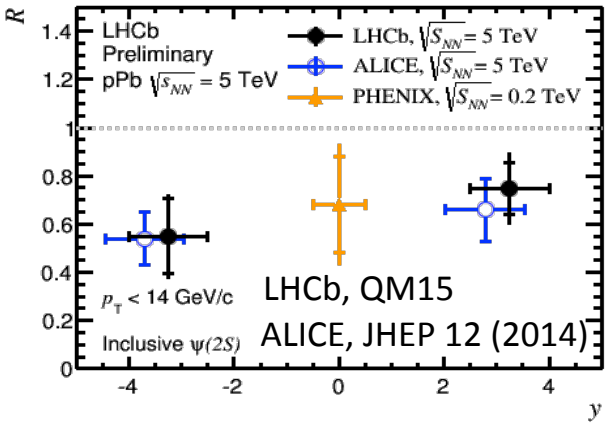



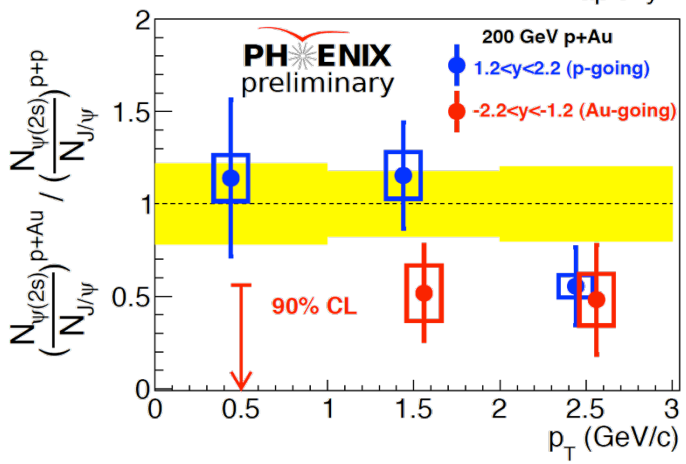

- Even with raw data, clearly the ψ' yield is suppressed relative to J/ψ in the Al going direction.

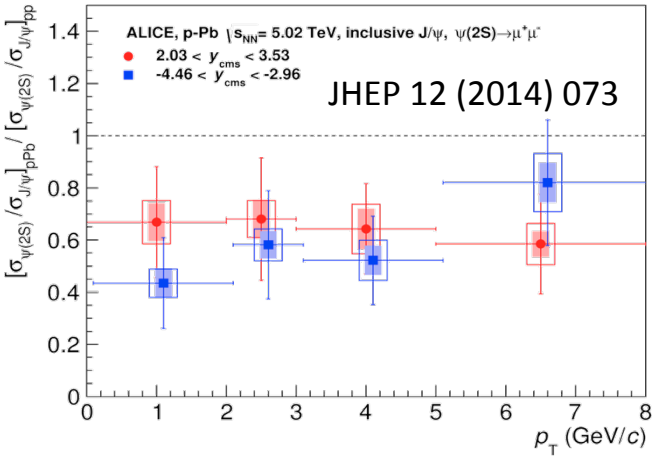
# Comparison with the LHC results

- Similar suppression trend for the rapidity dependence. More suppression in LHC especially in the forward rapidity?



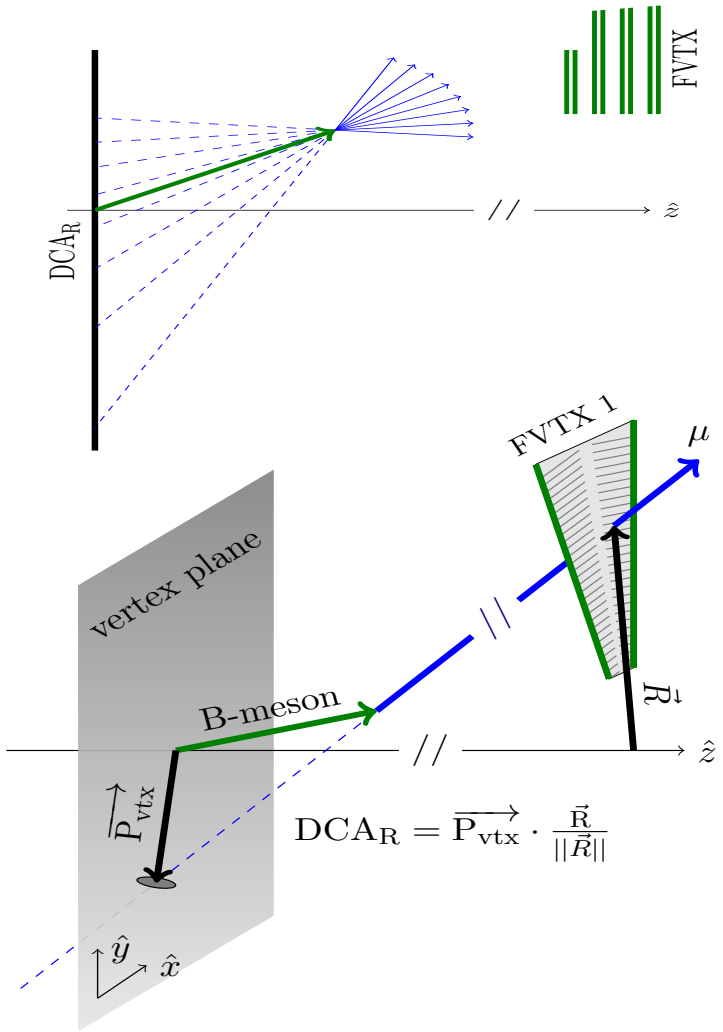




- Larger co-mover contribution in the LHC era? Gluon saturation change spectroscopic charmonium states ?

# Distance of Closest Approach (DCA) definition

- Definition of the $DCA_R$.

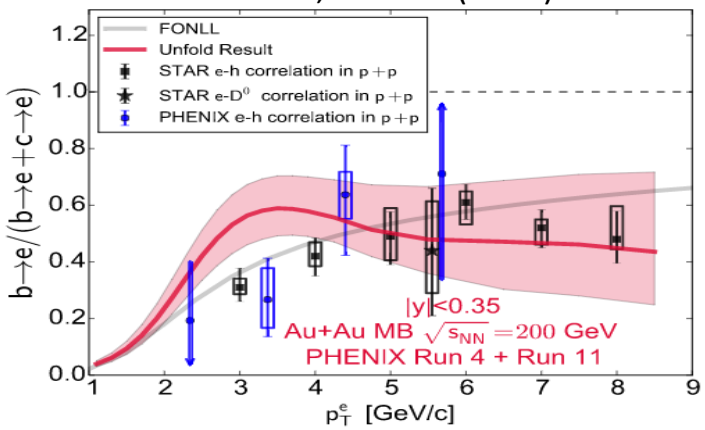



- Track projection to the primary vertex xy plane. The projection ($x_{proj}$, $y_{proj}$) and the primary vertex ($x_0$,$y_0$) forms the DCA vector ($x_{proj}$-$x_0$, $y_{proj}$-$y_0$).
- For p+p data, we use the beam average $x_0$, $y_0$ values.
- We define $DCA_R$ is along the direction of the detector radial direction.

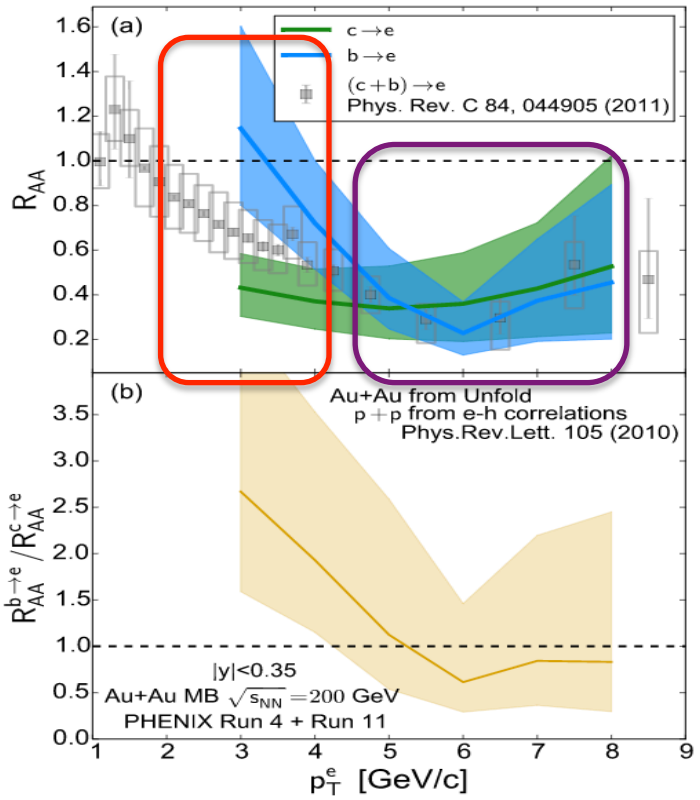
# Study the Hot Nuclear Matter effect via D/B production

- The bottom fraction has different $p_T$ dependence between p +p collisions and Au+Au collisions.

PRC 93, 034904 (2016)




PRC 93, 034904 (2016)



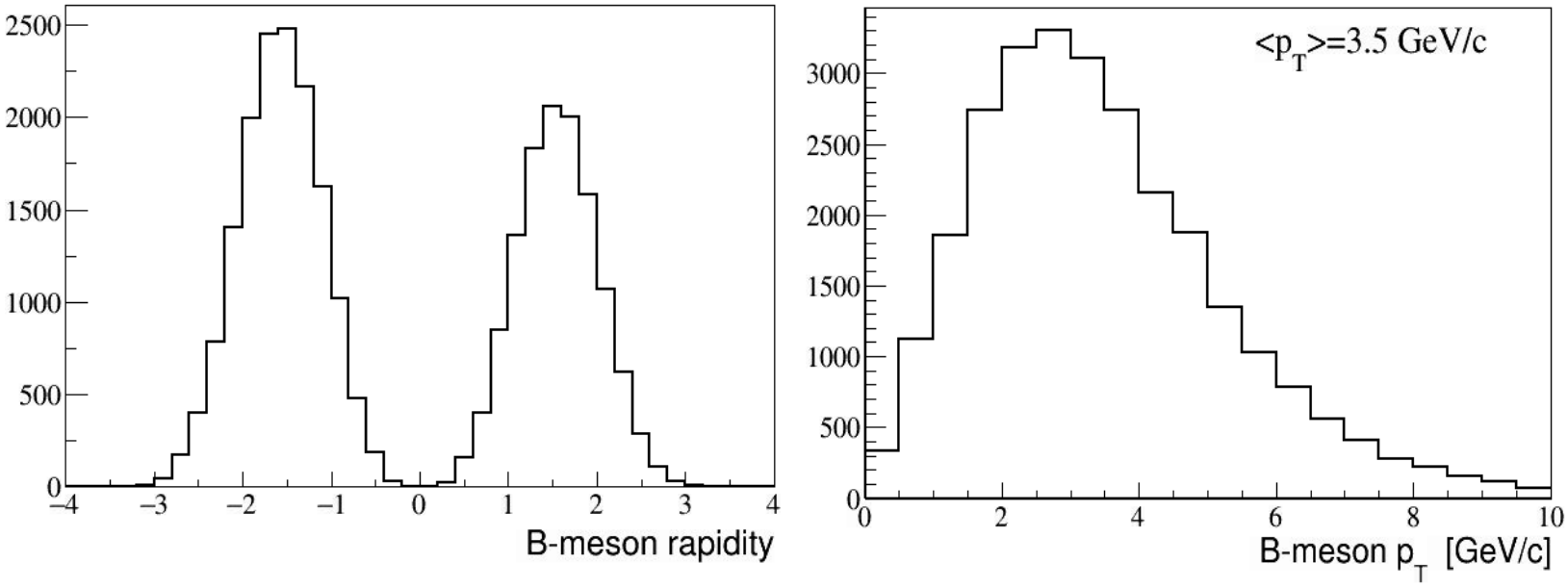

- From the $R_{AA}$ results,
  - Bottom has similar suppression as charm for high $p_T$ region.
  - Bottom may be less suppressed in the low $p_T$ region.

- New analysis with the high statistics run14 Au+Au data is ongoing.

# Can we measure B meson in forward rapidity?

- PHENIX provides good access to low $p_T$ B mesons via B to J/ψ decay channel in the forward and backward rapidity in both p+p and heavy ion collisions.

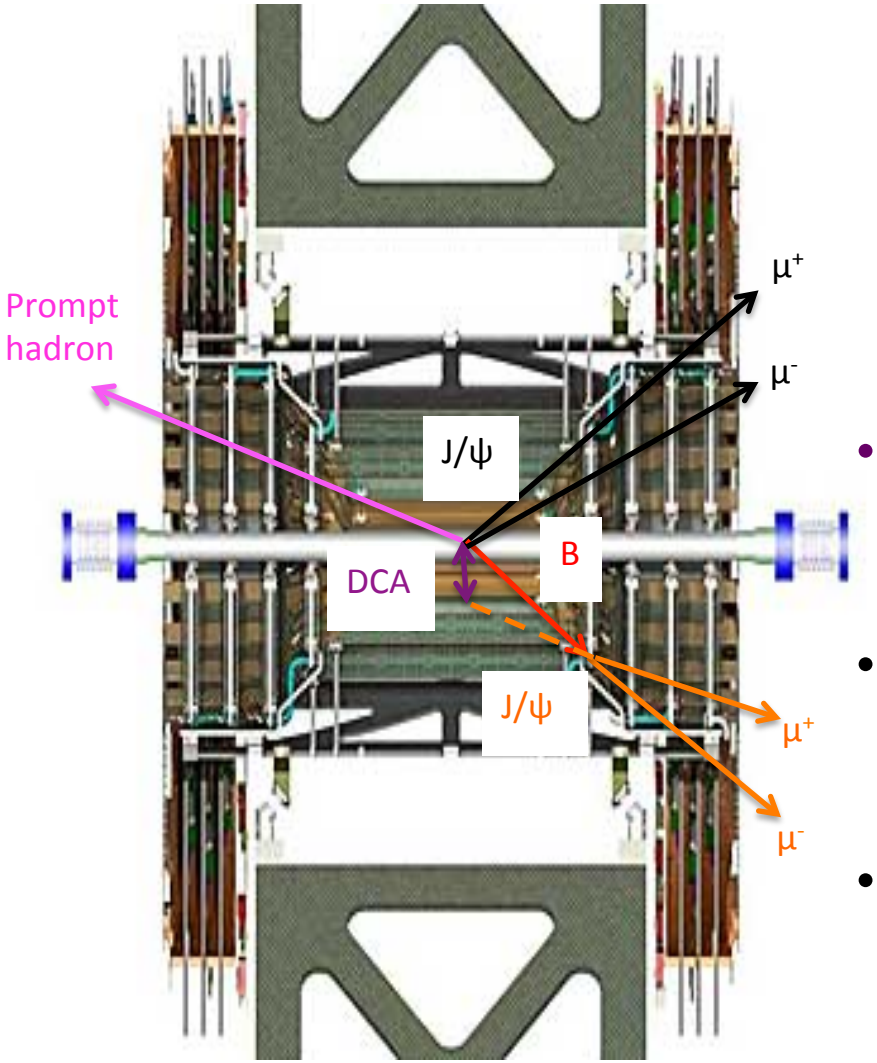
Kinematics of B mesons probed by PHENIX FVTX in PYTHIA simulation

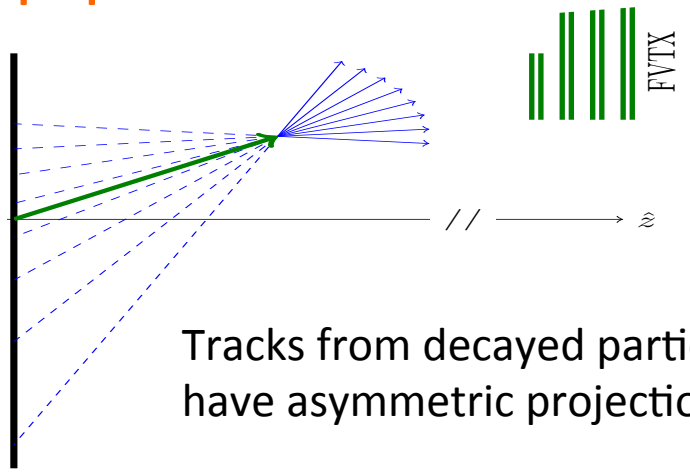



- B mesons measured in the forward/backward rapidity with longer decay length may probe different QGP evolution stage in heavy ion collisions from the mid-rapidity region.

# Can we measure B meson in forward rapidity?

## B->J/ψ->$\mu^+\mu^-$



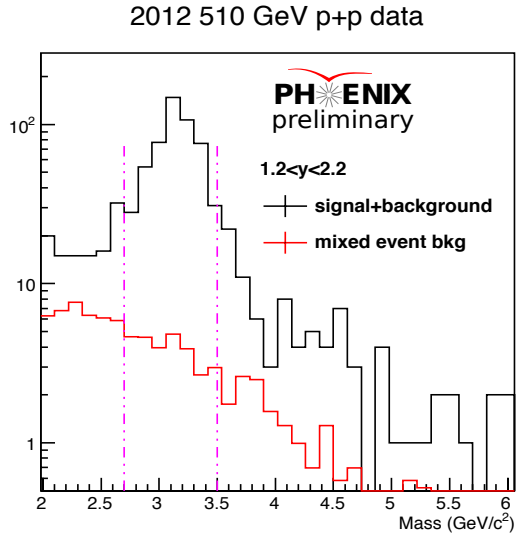



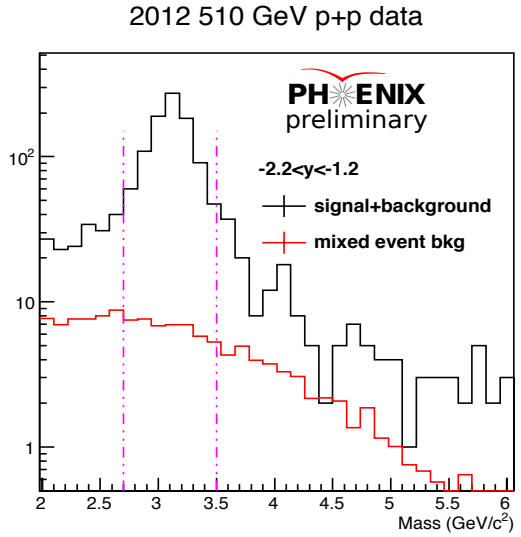

Tracks from decayed particles have asymmetric projection.

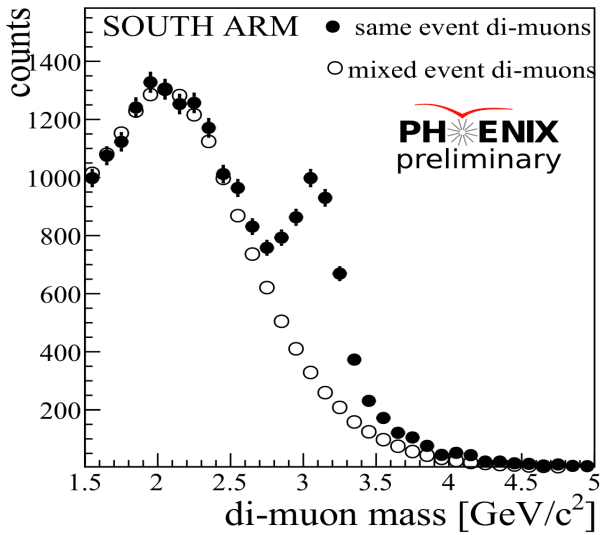
- Distance of Closest Approach (DCA) of track projection in the xy plane from the primary vertex.
- DCA has better resolution in radial (r) than azimuthal (ϕ) direction. Use DCA(r) for this analysis.
- Different DCA(r) shapes of prompt particles and decayed particles make the separation of B decayed J/ψ and prompt J/ψ feasible.

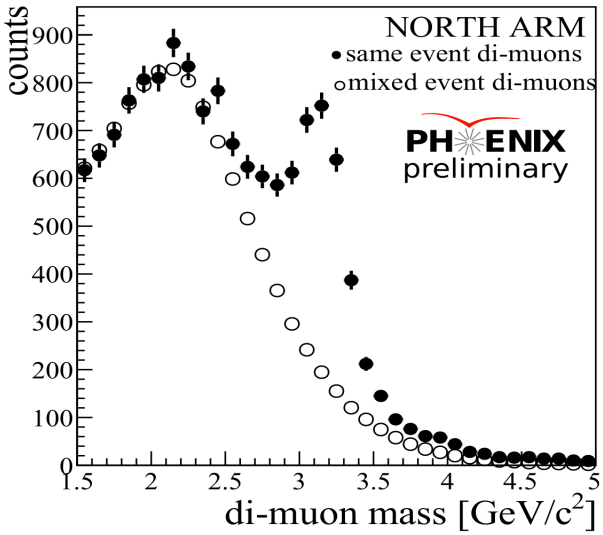
# Invariant mass of di-muons

- In 2012 510 GeV p+p (top) and Cu+Au (bottom) data.



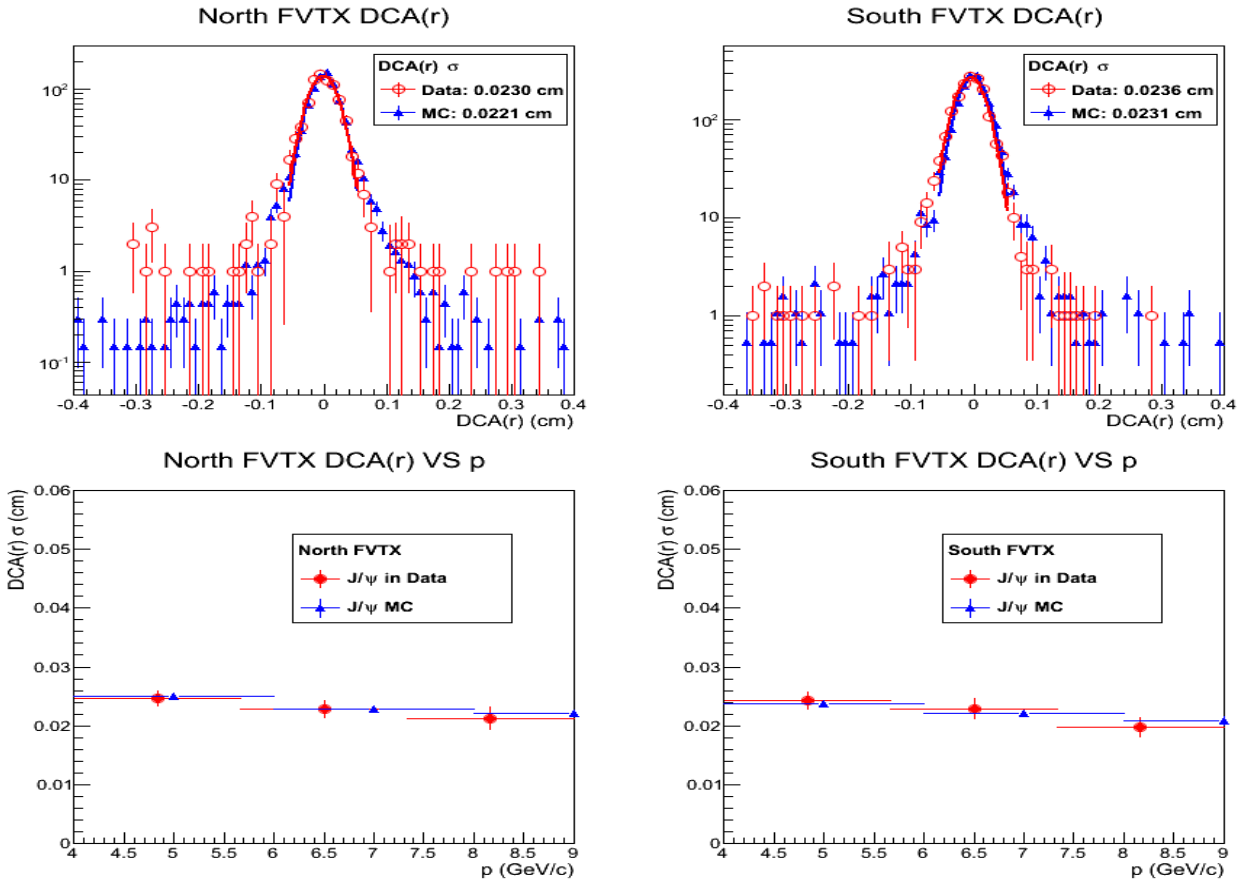



# Comparison of DCA(r) between data and simulation (p+p)

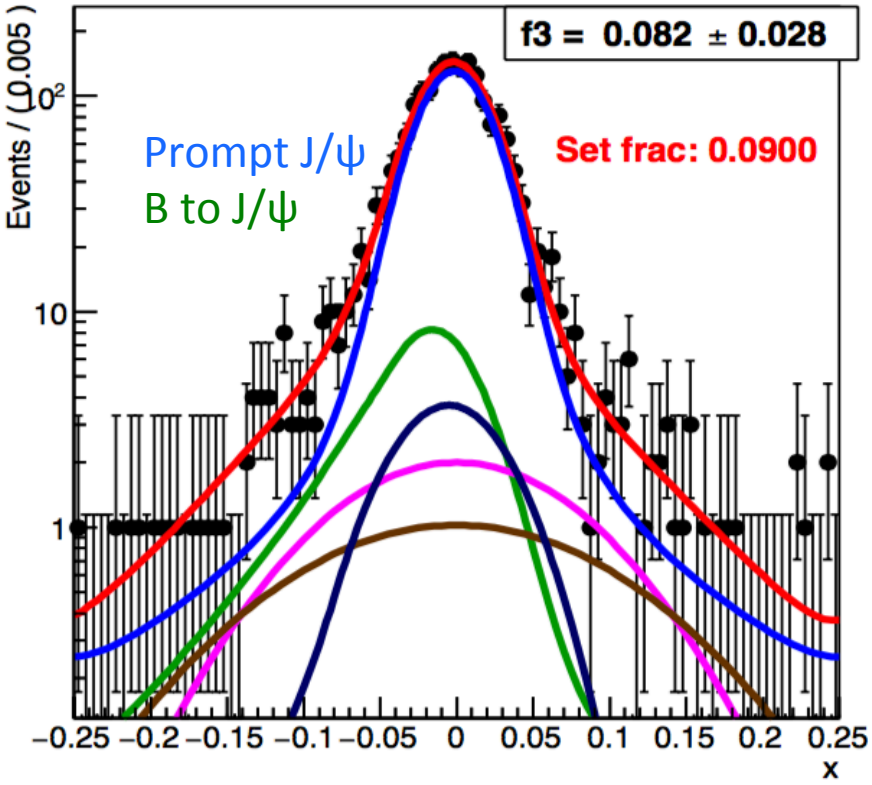
- DCA(r) of J/ψ decayed muons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.

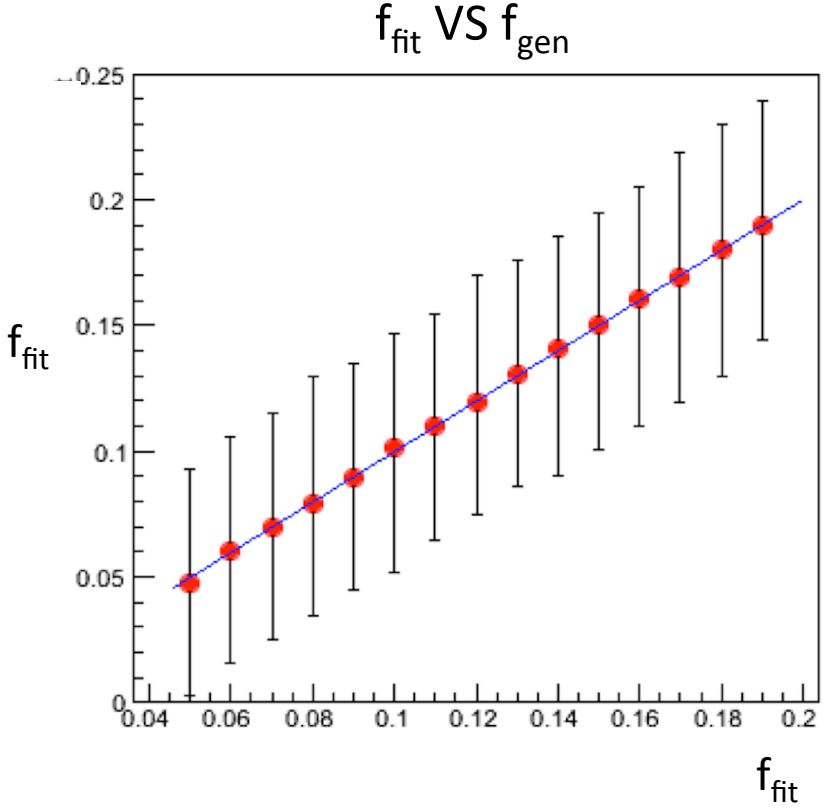



- Good agreement between data and simulation for DCA(r) resolution.

# Test the fit package in Toy MC

- Generate pseudo-data according to the shape of foreground and background. Use the same fit packages applied in data.

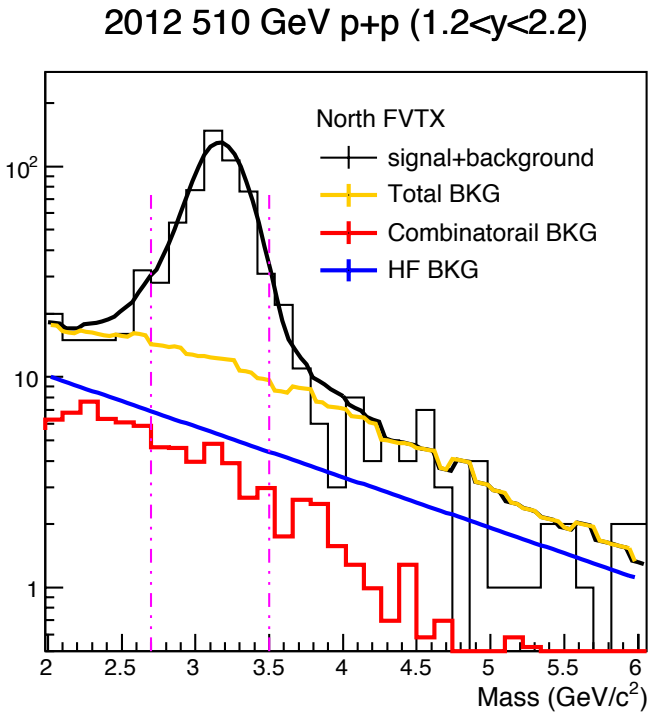


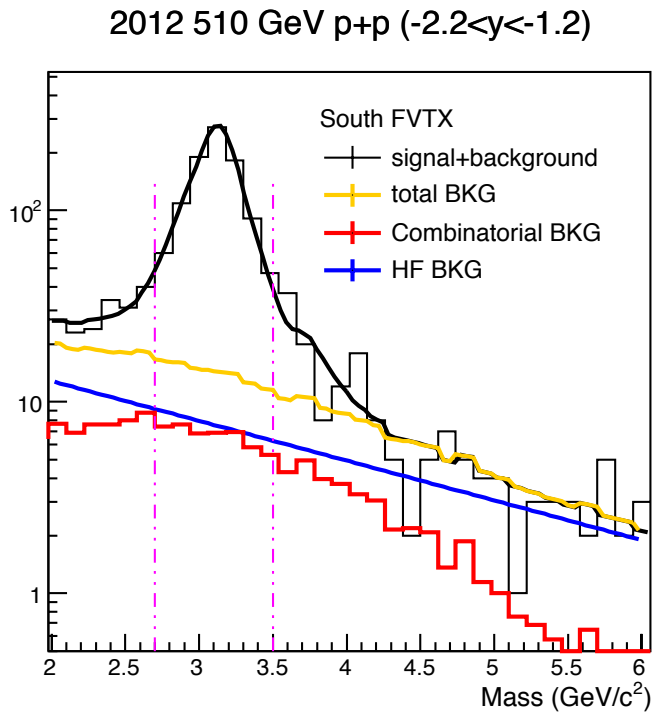




- Good linearity between generated and B to J/ψ ratio.
- Final results from data are under collaboration review.

# HF continuum background fraction

- Fit the di-muon mass to extract the HF continuum background.



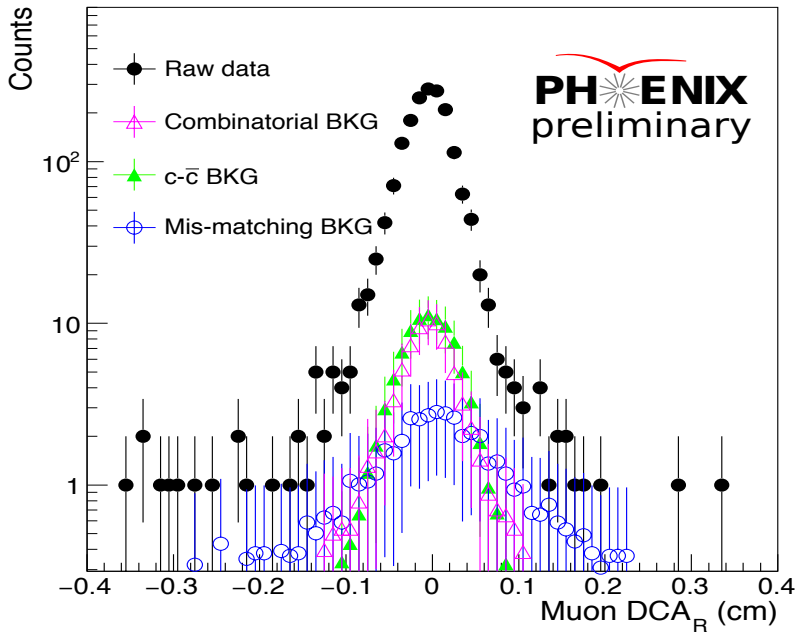




- Total background (10.1%) only consists of HF continuum background (4.7%) and mixed event background (5.4%).
- HF continuum background is comparable with the mixed event background within the mass cut window.

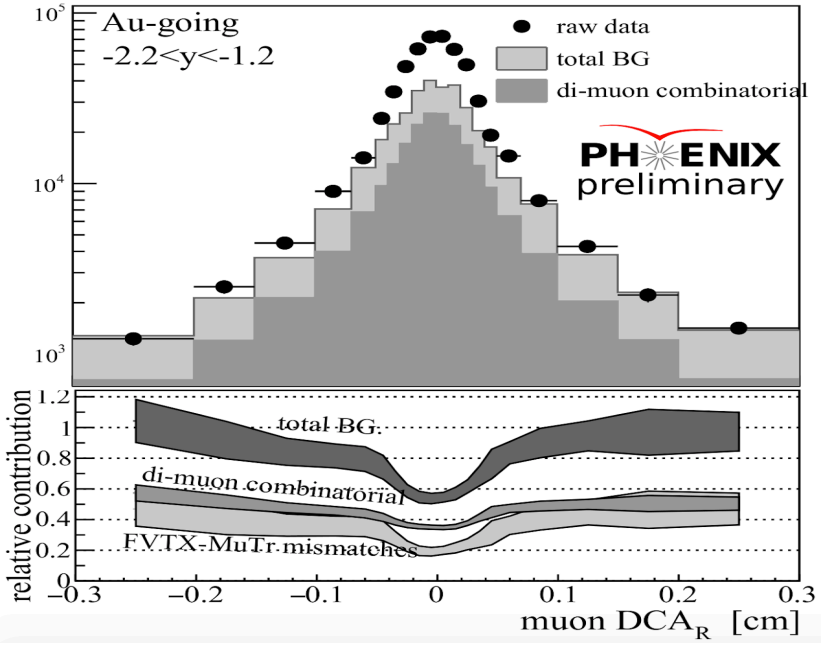
# Analysis strategy for the B to J/ψ ratio measurement (II)

- Background determination
  - Dimuon combinatorial background using mixed events.
  - FVTX-Mutr track mis-matching using topological detector event mixing technique.
  - Heavy flavor continuum (dominated by ccbar), generated in simulation with fraction determined in data.

2012 510 GeV p+p (-2.2<y<-1.2)

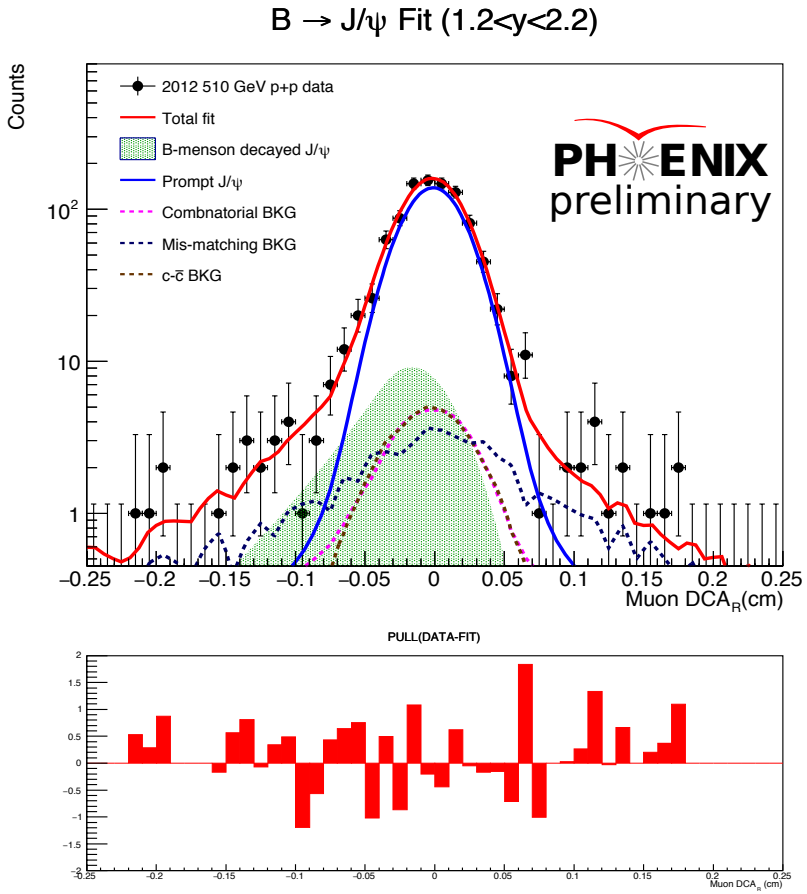


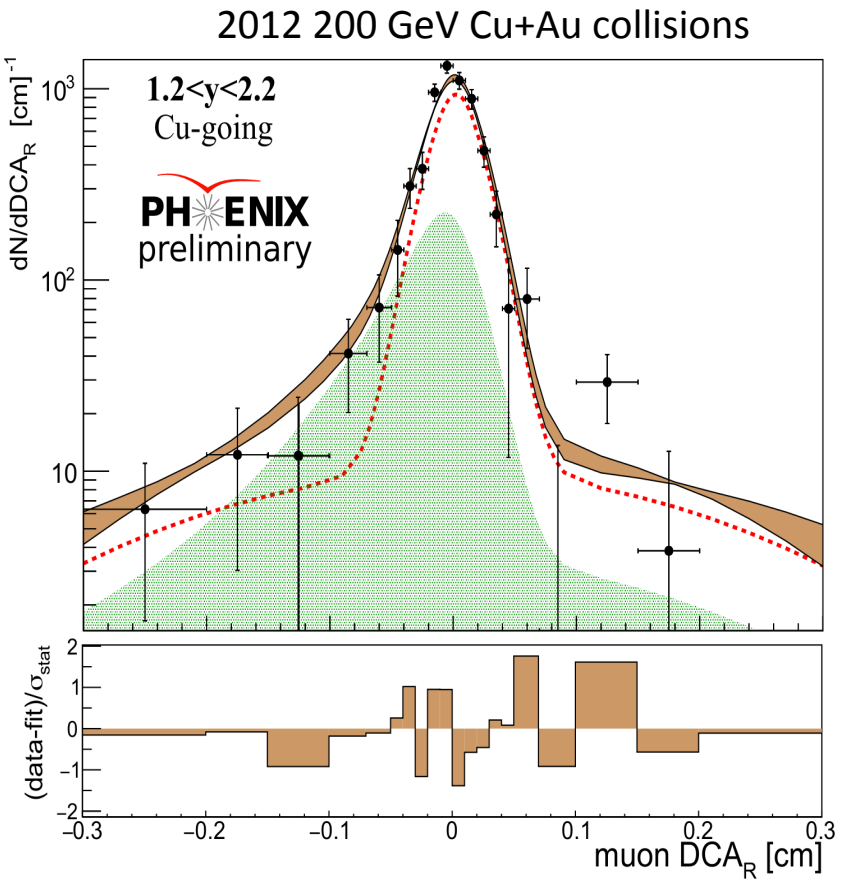

2012 200 GeV Cu+Au collisions



# Analysis strategy for the B to J/ψ ratio measurement (III)

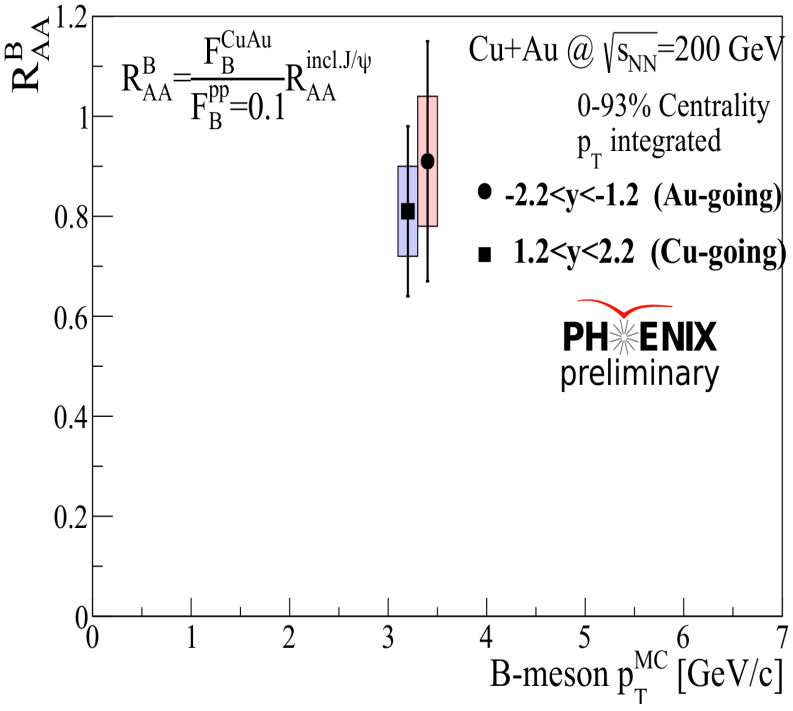
- Fit on $DCA_R$ in data to simultaneously determine the prompt J/ψ and J/ψ from B-meson decay yields and extract the B to J/ψ fraction.

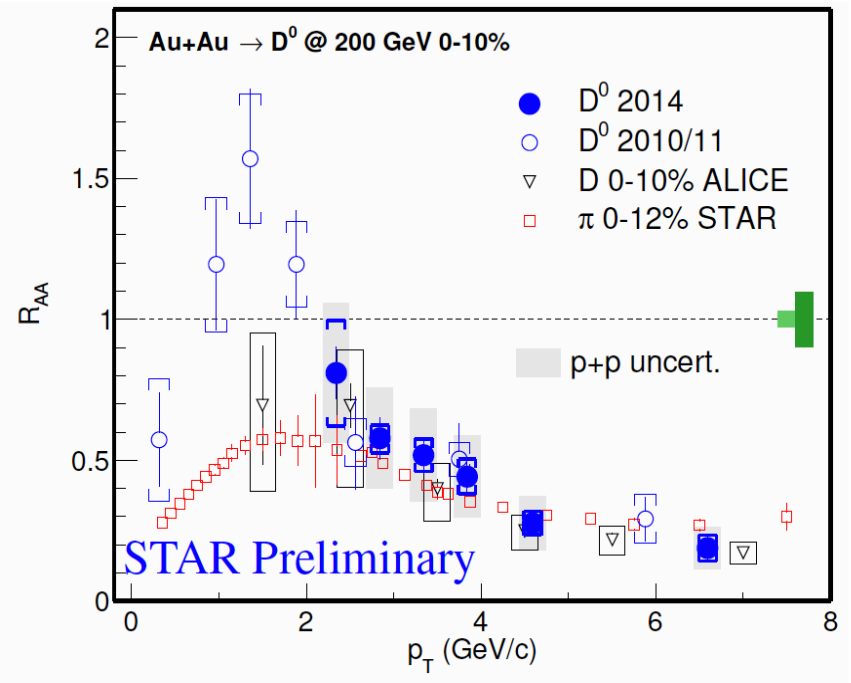


# B->J/ψ $R_{AA}$ in 200 GeV Cu+Au data

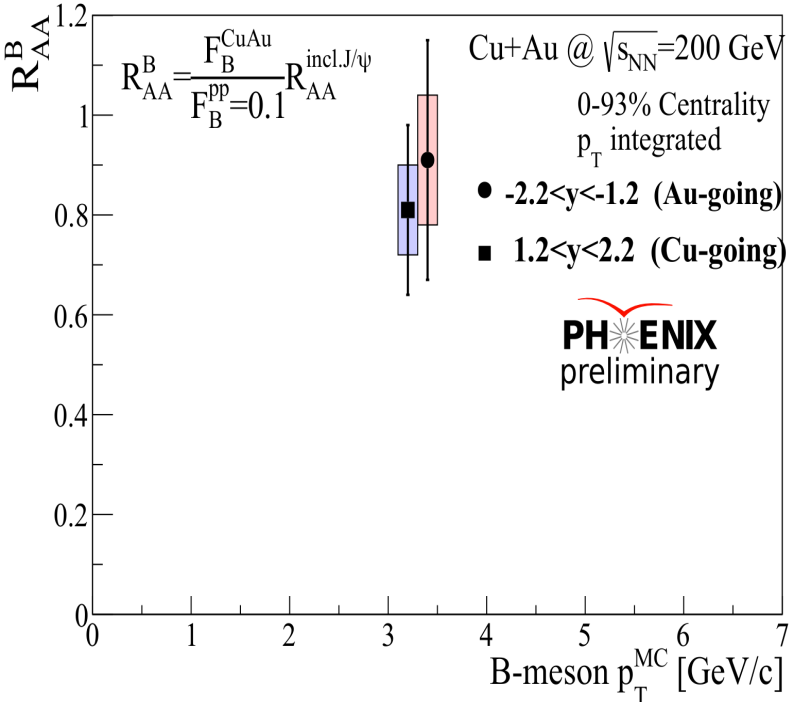
- Cu-going/Au-going B-meson $R_{CuAu}$ measured in Cu+Au data agree with mid-rapidity Bottom decayed electron $R_{AuAu}$ result at the same energy.
- Is bottom production less suppressed than charm production in the forward rapidity in the low $p_T$ region?



# B->J/ψ $R_{AA}$ in 200 GeV Cu+Au data

- Cu-going/Au-going B-meson $R_{CuAu}$ measured in Cu+Au data agree with mid-rapidity Bottom decayed electron $R_{AuAu}$ result at the same energy.
- Qualitative agreement with theoretical calculations for Au+Au and Cu+Cu collisions at mid-rapidity.




Ivan, PLB649, 139 (2007)